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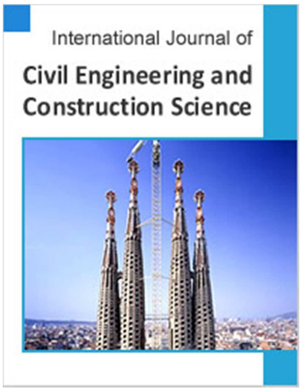


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# Smart Materials and Their Applications in Civil Engineering: An Overview

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## Abstract
A human endeavor to achieve the limits of his concept of the longest, tallest and deepest has led to the global quest for unmatched excellence in new construction materials. The decreasing availability of suitable construction materials is putting pressure on the engineers and designers to think about methods of utilizing intelligent materials. With the advent of advanced technology, smart materials are used in various civil engineering applications and across a wide range of other sectors including agriculture, aerospace, marine, food and packaging, healthcare, sport and leisure, energy and environment, space, and defence using embedded fibre optic sensors. Smart materials technology being a relatively new can indeed create high value-added opportunities and has a strong innovative content if well supported. Smart materials under different temperatures exhibits unique characteristics of shape and superelasticity, which suit in varied applications in civil engineering infrastructures. Smart materials are capable of sensing their environment and can respond accordingly. The scope of this paper is limited to the brief overview of the technology, material requirements, classification of smart materials, smart structures and their applications. The insights gained by gathering data on smart materials have found a large number of applications in civil engineering practice.

## 1. Introduction

Historical ages are often referred to in terms of material age such as, Stone-age, Bronze-age, Iron-age etc. The present age is considered to be the age of flexibility of choice of materials. Scientific and technological developments have given us numerous advanced and novel materials and their applications, and any one single material, therefore, can not characterize the present age. Today, due to the scarcity of suitable construction materials, the primary concern of engineers is to explore the new advanced materials which find their bulk utilization in various engineering applications. For the development of such innovative materials and their use, the engineer has to select the most appropriate technology, he must know what properties should be considered, how these are determined, what are their limitations, and should intelligently select the right material for appropriate use. These predictions are not the result of gazing into a crystal ball, but are based on an appraisal of current research in leading materials laboratories around the world. In discussing the possible materials of tomorrow's world, it is not enough to consider current research. In a dynamic world of changing political frontiers, shrinking distances, widening information networks, and growing environmental concern, attitudes to the production and use of materials will also change, probably radically. All current trends in materials research point to a much more efficient use of right materials in the various fields of engineering practice in the future. For materials, which are becoming scares, this approach is obvious and research must aim to find alternative materials to replace the old ones. Materials of the future will be produced more efficiently than ever before, with emphasis on fewer operations and much less wastage in producing the final shape. In other words, tomorrow's material will provide the basis of a manufacturing technology that is more energy-conscious and environmentally responsible than today's in terms of both material production and application. Thus, a human endeavor to achieve the limits of his concept of the longest, tallest and deepest has led to the global quest for unmatched excellence in new construction materials. The decreasing availability of stable construction materials is putting pressure on the engineers and designers to think for methods of utilizing even the poorest of these materials. The advent of advanced materials technology, smart materials have revolutionized their use in various civil engineering infrastructures [1-4]. Today, researchers and designers are focusing on smart materials for their unique properties and performance in civil engineering applications, and across a wide range of sectors including agriculture, aerospace, marine, food and packaging, healthcare, sport and leisure, white goods, energy and environment, space, and defence using embedded fibre optic sensors. Smart materials technology being a relatively new can indeed create high value-added opportunities and has a strong innovative content if well supported and exhibit extraordinary ability in performing their design function. Smart materials are capable of sensing their environment and can actuate in order to perform their functions either in closed loop smartness or in open loop smartness. Many researchers [5-8] have reported classifications and applications of smart materials in various engineering infrastructure projects, yet there is need for overview of applications of smart materials in civil engineering. Therefore, in this paper, an attempt has been made to present the brief overview about the smart materials and the scope of the paper is limited to the simple overview of the technology, material requirements, classification of smart materials, smart structures and their applications and potential benefits. The insights gained by gathering data on smart materials have found a large number of applications in civil engineering practice.

## 2. Characteristics of Smart Materials

A smart material is one which possesses unique properties and responds to a change in its environment. Generally, smart materials exist in two phases at different temperatures such as [9]:

1. Austenite phase, which exists at high temperature, and
2. Martensite phase, which exists at low temperature.

Due to change in either temperature or loading conditions, the smart material exhibits many unique properties during the transformations between these two phases, such as shape memory effect, superelasticity effect, and two-way memory effect, etc. Smart materials are the next frontier in engineering and manufacturing, which are poised to emerge in a wide range of industrial applications (Fig. 1). The applications of smart materials and structures have been recently extended to civil infrastructures as advances in sensing, networking, continuous monitoring and control of structural functions a realizable goal. The majority of research focused on the intelligent civil structure has been in the following two areas:

1. Identification of structural behavior or properties (e.g., deformation, energy usage, damage evaluation); and
2. Control of structural response to external (e.g., wind, earthquake) or internal (e.g., acoustics, temperature variation) stimuli.

Due to the complexities of civil structures, such as massive size, presence of nonstructural components, subjection to random excitations, and diverse functionality, investigation of the intelligent civil system has become a challenging and fruitful research area. Some recent structural failures due to natural events such as the earthquakes - Bhuj 2001, Sumatra 2004 and Kashmir 2005, hurricanes in the Southeast, and blizzards in the Northeast and Midwest have amply demonstrated the need for rapid assessment of structural integrity after such events as well as a need to control and minimize damage. The field of smart structures is an emerging engineering field that has captured the attention of many engineering professionals and academicians in recent years. A smart structure incorporates "smart material" sensors and actuators, electronic signal processing, and advanced control systems to produce appropriate actuator response for particular sensor inputs. Smart materials are materials that possess adaptive capabilities to external stimuli. Such materials include materials fabricated to incorporate embedded computing tools such as sensors and microprocessors, but they also include new classes of structural materials that offer the opportunity to revolutionize many aspects of civil engineering construction. High-performance materials can be introduced as building media for entire structures or selectively used in critical components of a structure. Examples of the former include applications of high-performance steel, concrete, or fiber reinforced plastics for structural frames, cement-based soil-mixing for site modification, etc. Examples of the latter might include special protective-devices, such as seismic isolators and dampers, geosynthetic membranes, etc. These smart materials provide an important opportunity for the design of new structures and the rehabilitation of aging or damaged structures. These materials promise easier, less costly, and more durable construction than conventional materials.

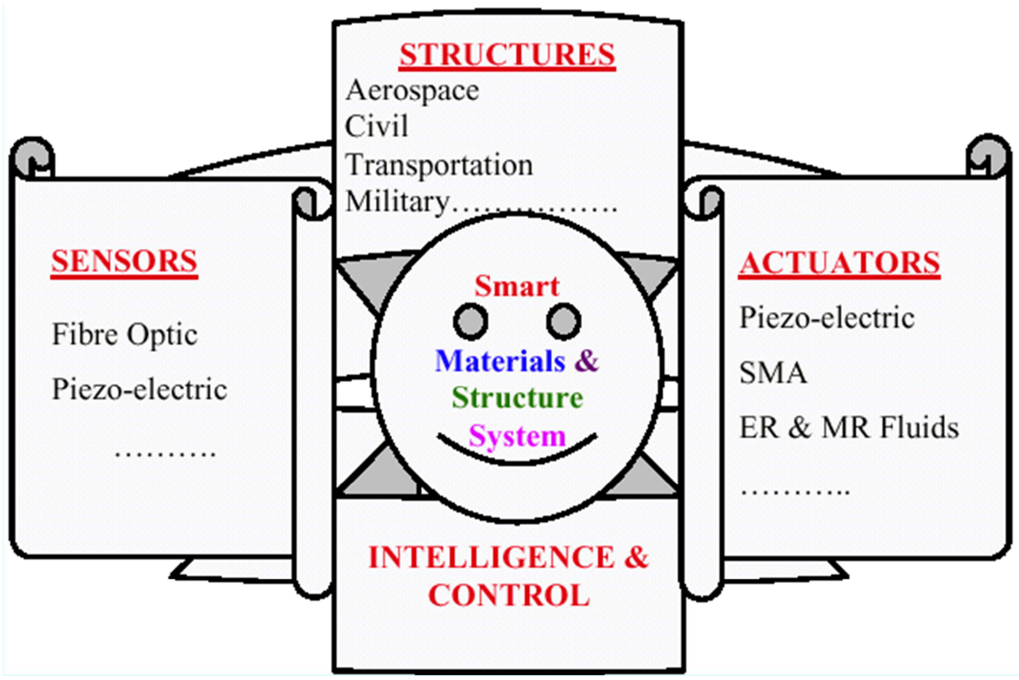


***Figure 1.*** *Smart materials and structural system.*

## 3. Need for Smart Materials

The decreasing availability of suitable construction materials is putting pressure on the Engineers and Designers to think for methods of utilizing intelligent materials. The developments of these materials have triggered off worldwide research programs and continued conventional and non-conventional applications leading to ultimate economy. Thus, a human endeavour to achieve the limits of his concept of the longest, tallest and deepest has lead to the global quest for unmatched excellence in new construction materials such as "Smart Materials".

Smart materials have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields. Nowadays, technology is devoted to the development of new materials able to satisfy specific requirements in terms of both structural and functional performances. Smart materials could also be used in the monitoring of defence activities to defend the country and its vital interests, and to participate actively in peacekeeping and peace restoration missions. Thus, there is a dire need of exploring new smart materials, which will help us in keeping pace with other developed countries in the various fields of engineering and technology. Significant breakthroughs are expected in new composite materials especially in those applications, such as electronic, optic and biomedical, where functionality is the most relevant technical need. Key areas of focus for the development of smart structures to include [10-11]:

a) Application of smart materials in new construction infrastructures
b) Structural health monitoring, control and lifetime extension (including self-repair) of structures operating in hostile environments
c) Thermal management of high temperature turbines for power generation.

*Material Requirements*

Using smart materials for achieving a desired goal for a particular application, the following specific properties are to be fulfilled:

a) Mechanical properties - such as strength behavior
b) Behavioral characteristics - such as material health behavior
c) Technological properties - such as mull-function free and maintenance capabilities
d) Economic criteria – such as efficient and cost effective material based on its applications
e) Environmental characteristics – such as pollution free and most environment friendly product for sustainable development of infrastructures

## 4. Classification of Smart Materials

Smart materials are the products of advent of new emerging science and technology. The advent of smart materials has revolutionized their use in numerous infrastructural systems and are also picking up at an unprecedented pace. Smart materials can be classified into the following categories (Fig. 2), which can be used either as Sensors or Actuators or both. Some of these smart materials are briefly outlined as below:

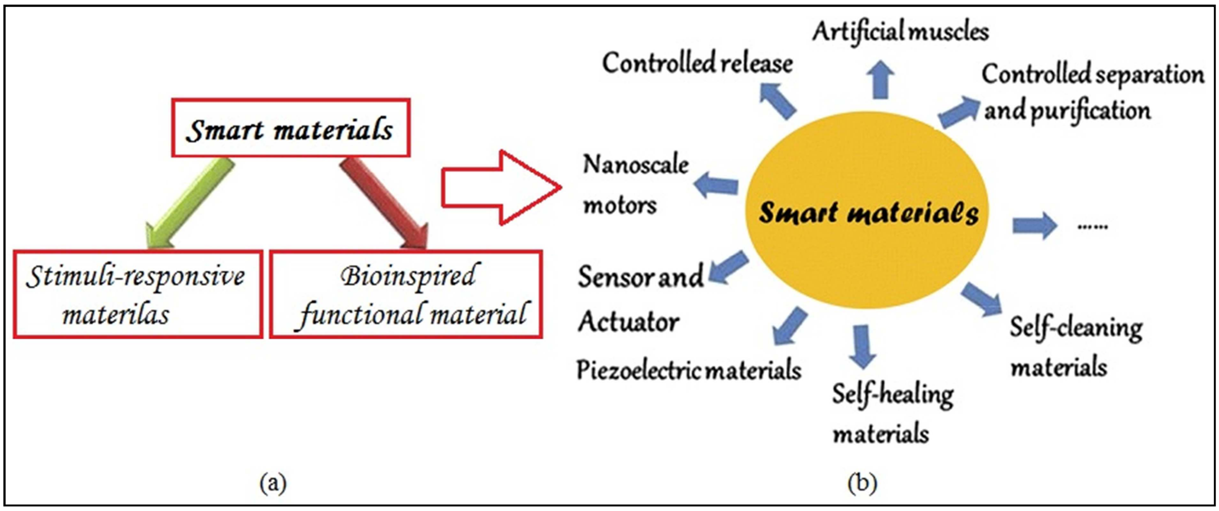


***Figure 2.*** *(a). Classification of the smart materials, (b). Various applications of smart materials.*

### 4.1. Sensors and Actuators

Sensors and actuators are intelligent elements, which adjust themselves with environmental changes on account of any sort of interaction. Unlike transducer which transforms one form of input (energy) into another form, sensors and actuators have mimicked nature to a large extent. With emerging new technology, visual/optical, acoustic/ultrasonic, electrical, chemical and thermal/magnetic sensors have been developed for use in various industrial applications. The response from these primary sensors is converted to electrical signals through central processing unit for making appropriate decision based on these inputs. The above phenomenon can also be performed manually by an operator who has gained experience and understanding of knowledge of smart technology. However, in such a case, a pertinent information is require to aid the operator in making a more judicious decision. Therefore, to avoid any uncertainty, a smart machine capable of making sound judgment has to be developed such as sensors and actuators. A simplified block diagram of sensors and actuators is shown in Fig. 3.

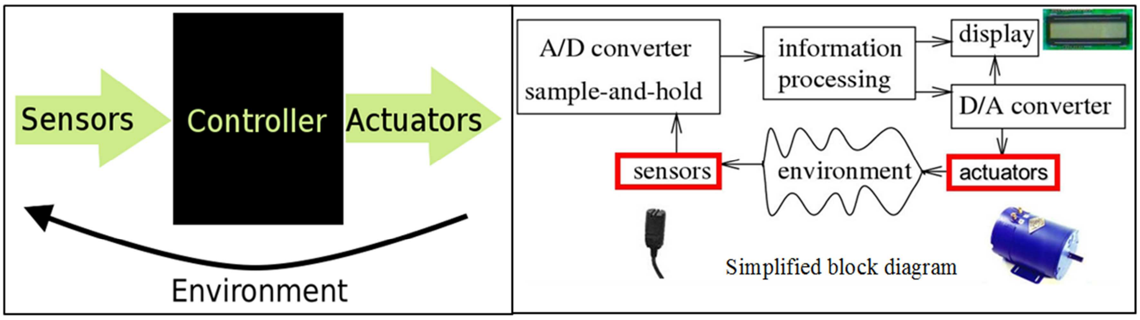


***Figure 3.*** *Simplified block diagram illustrating sensors and actuators.*

There has been a very competitive struggle between Electronics and Optics technologies for development of sensor and actuator systems. However, Optics technology has turned out to be more competitive in developing more efficient sensors compared to electrical sensors. Optics sensors are more advanced and efficient and are fire hazard free products. However, electrical sensors have an upper edge as being available at lower costs and available in abundance compared to optic sensors. Another prominent feature of optical fibers is that these are more recently developed with high sensing capabilities and dominated in the communications industry, whereas, electrical sensors are dominated in the processing and actuating technologies. Thus, this competition has a lot to offer in development of novel sensor-processor - actuator systems. When a structure at its reference state is subjected to application of loads, it transforms into another stable state. The difference noticed in configuration between these two states is called the response of the smart of intelligent structure. The quantities measuring these differences are called response quantities corresponding to the excitation. The devices that make the measurement are known as Sensors. Fibre Optic sensors and piezoelectric materials [12] are two of the primary smart products being tried by reseasrchers for in the various industrial applications. The fibre optic sensors can be categorized as:

a) Global Sensor

Global Sensor, which comprises of Optimal Time Domain Reflectometry and Fibre Optic Polarimetric Sensors, monitor the overall health status of the structural component against global warning system.

b) Discrete Sensor

Discrete Sensors, which comprises of Extrinsic Fabry-Pero

Interferrometric Sensor and the Bragg grating strain Sensor, which analyze quantitative values at different locations against any damage in respect of size, location and severity.

### 4.2. Piezoelectric Materials

These materials [13] exhibit change in their linear shape when subjected to an electric field, which makes the material expand or contract almost instantly. A schematic illustration of the piezoelectric effect is illustrated in Fig. 4 [14]. When integrated into a structural member, a piezoelectric material generates an electric field in response to mechanical forces, which is known as the direct piezoelectric effect and vice versa is the so-called converse piezoelectric effect (Fig. 4a). Figure 4b shows a hybrid-fiber nano-generator based on the piezoelectric effect, which comprises zinc oxide nanowires and a poly vinylidene fluoride polymer around a conducting fiber. These events are called the direct and converse effects, which are of interest in the field of structural sensing and the converse piezoelectric effects can be used for control. These materials have potential use in various applications with higher degree of accuracy and high speed end products.

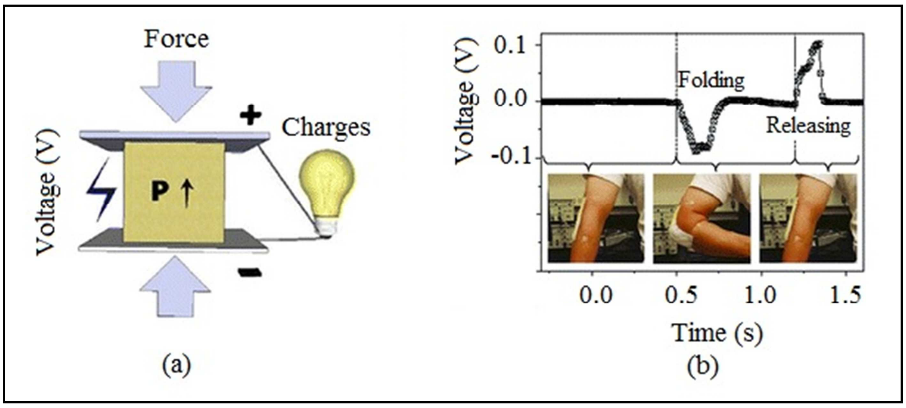


***Figure 4.*** *(a). A schematic illustration of the piezoelectric effect, (b) A hybrid piezoelectric structure for wearable nanogenerators attached on a human arm.*

### 4.3. Electrostrictive and Magnetostrictive Materials

These materials exhibit mechanical change in proportional to the square of the electric field, which refers to the material quality of changing size in response to either an electric or magnetic field, and conversely, producing a voltage when stretched. These materials show promise in applications ranging from pumps and valves, to aerospace wind tunnel and shock tube instrumentation and landing gear hydraulics, to biomechanics force measurement for orthopedic gait and posturography, sports, ergonomics, neurology, cardiology, and rehabilitation.

### 4.4. Rheological Materials

Rheological materials are smart materials, which comprises of not only solids but also fluids and find their application in shock absorbers, dampers for vehicle seats and exercise equipment, and optical finishing.

### 4.5. Shape Memory Alloys

Shape Memory Alloys [15] possess a unique property by which the metal reverts to its original size or shape at a characteristic transformation temperature. These materials are prone to phase transformation under the influence of thermal field. These alloys find their applications in medical sciences, electrical, aerospace and mechanical engineering and also can open new applications in civil engineering specifically in seismic protection of buildings. They are useful in thermostats, automobile, plane and helicopter parts. Currently, Shape Memory Alloys are mainly applied. Their properties, which enable them for civil engineering application, are- repeated absorption of strain energy without permanent deformation, for obtaining wide range of cyclic behavior, to resist fatigue resistance under large strain cycles, and due to their great durability and reliability in the long run.

### 4.6. Electrochromic Materials

Electrochromic Materials inherent a unique property for changing their optical properties under the effect of voltage applied across it [16]. These materials are used as antistatic layers, electrochrome layers in LCDs (liquid crystal displays), and cathodes in lithium batteries.

### 4.7. Smart Gels

Smart gels have high ability of absorbing or releasing fluids and possess inherent properties of swelling and shirking under the influence any chemical or physical stimuli. The potential engineering application of smart gels include in agriculture, food, drug delivery, prostheses, cosmetics, and chemical processing.

### 4.8. Mechatronics

Mechatronics is a multidisciplinary field of science and technology is a design process to create more functional and smart products (Fig. 5). These smart devices have crept into everyday life such as- Robots, Anti-lock brakes, a sophisticated control system takes over the braking function when the sensors recognize one or more wheels are locking up, Photocopiers, Computer disk drives, Humidity sensitive clothes dryers and windshield wipers. The potential use of mechatronic smart devices can be found in various applications such as medicines, agriculture, buildings, automobiles, entertainment industry and intelligent aids for the elderly and disabled ones.

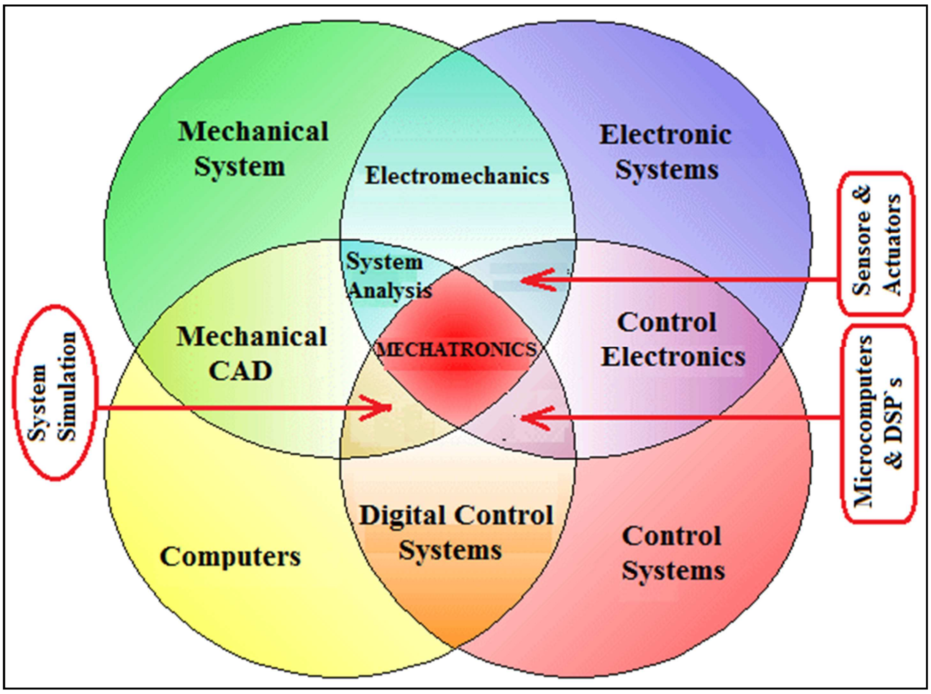


***Figure 5.*** *Multidisciplinary Constituents of Mechatronics (www.engr.ncsu.edu/mechatronics).*

### 4.9. Ken Materials

Though, Mechatronic smart have been used in many interdisciplinary fields of engineering, yet these created many issues of complexity of the end products. To overcome these complexities, alternative smart devices known as ken materials have been developed. These materials find their potential applications in concrete technology to monitor concrete structures, thereby minimizing the complexity of the Mechatronic system

### 4.10. Materials with Added Functions

Smart materials with added functions can be incorporated into structural system components as embedded sensors and actuation elements, which are capable of modifying structural behavior in response to external stimuli. The most potential smart materials that have been examined in recent years are thermoresponsive materials, piezoelectric materials, electrorhelogical fluids and more recently, magnetorhelogical fluids.

## 5. Applications of Smart Materials

Conventional engineering structures operate at their limited performance compared to smart materials, which have an increasing range of applications in the following fields:

a) In construction of smart buildings, for environmental control, security and structural health monitoring, cable-stayed bridges and reduce the effects of earthquakes.
b) In marine and rail transport applications for strain monitoring using embedded fibre optic sensors, Smart textiles for everyday wear and for health and safety purposes.
c) In Military Applications, for Smart Skin, Smart Aircraft, Autonomous Smart systems, Stealth Applications etc.

### 5.1. Composite Smart Material

To utilize the best properties of a composite material, two or more individual smart materials are combined together, which is known as composite smart material. The most commonly used composite smart materials are:

a) A man-made designed composite smart material to improve or add strength or stiffness, which has more adaptability in the design requirements.
b) A composite smart material prepared with Fibre/Reinforced Polymers, which have potential use as reinforcement for concrete, steel or other construction materials.

### 5.2. Smart Structural Systems

Generally, any conventional structural system is designed under pre-selected design loads and forces for any required purpose, which can not successfully develop its ability against unexpected loads and forces unless a large safety factor is provided for safety limit states to take into account various uncertainties in load and force amplitudes and structural response to seismic design. Therefore, a smart structural system is defined as structural system with a high-level of safety relying on the embedded smart devices that can automatically adjust structural characteristics, in response to the change in external disturbance and environments, toward structural safety and serviceability as well as the elongation of structural service life. The essential idea is to produce non-biological systems that will achieve the optimum functionality observed in biological and that emulates a biological system through emulation of their adaptive capabilities and integrated design. The basic concept and strategies for the development of smart structural systems should be established, and, the followings are the main targets of research and development:

a) Potential use and type of smart structural systems
b) Performance based smart materials or devices to be identified
c) Performance verification of proposed smart structural systems by computer simulations and experiments
d) Establish set of guideline for the performance evaluation of smart structural systems

A smart structure is a system that incorporates particular functions of sensing and actuation to perform smart actions in an ingenious way. The basic five components of a smart structure are illustrated in Fig. 6.

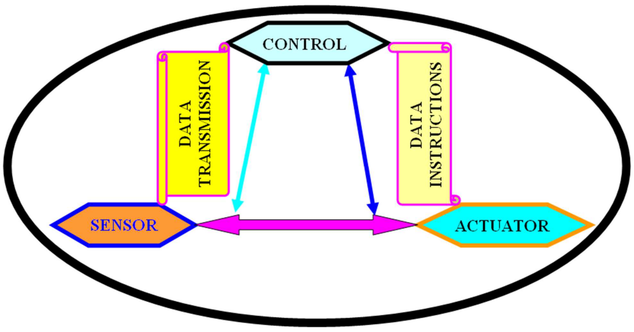


***Figure 6.*** *Components of a smart structure.*

# 6. Smart Structures in Civil Engineering Applications

Generally, any conventional structural system is designed under pre-selected design loads and forces for any required purpose, which can not successfully develop its ability against unexpected loads and forces unless a large safety factor is provided for safety limit states to take into account various uncertainties in load and force amplitudes and structural response to seismic design. Therefore, for more safety purposes, smart structures play a vital role as far as the safety requirements are concerned in the design of various civil engineering infrastructures. For example, smart devices help in monitoring of the current and long term behavior of any civil engineering structure, which would lead to enhanced safety during its life. Thus, this would influence the life costs of such structures by reducing upfront construction costs due to reduced safety factors in initial design and by extending the safe life of the structure by using smart materials.

## 6.1. Smart Concrete

Unlike conventional concrete, the smart concrete has higher potential and enhanced strength. Smart concrete can be prepared by adding carbon fibres for use in electro-magnetic shielding and for enhanced electrical conductivity of concrete [17]. Smart concrete under loading and unloading process will loose and regain its conductivity, thus serving as a structural material as well as a sensor [18]. Smart concrete plays a vital role in the construction of road pavements as a traffic-sensing recorder, and also melts ice on highways and airfields during snowfall in winter season by passing low voltage current through it.

## 6.2. Smart Buildings

A smart building is an intelligent space that will transform efficiency, comfort, and safety for people and assets. Smart buildings are those that incorporate sensors and intelligent systems to control building operations and facilities. Smart building integration is illustrated in Fig. 7. Smart Buildings with intelligent solutions enable the high-performance workplace e-business strategies. Therefore, a smart building requires sensors to detect and monitor the number, presence and flow of people for a number of different requirements. Smart buildings contain a high level of electronic microprocessor based control systems that operate a wide range of services such as lighting, heat, ventilating and air conditioning, power, vertical transportation, fire and life safety, and security. In recognition of the electronic aspects of an intelligent building, we can divide the operation into four categories:

a) energy efficiency
b) life safety systems
c) telecommunications systems
d) workplace automation

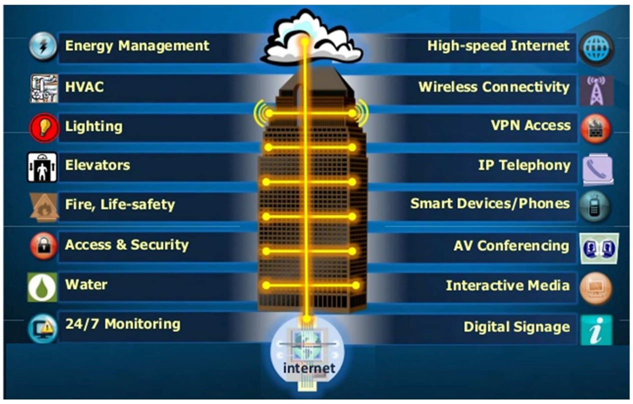


***Figure 7.*** *Illustration of smart building integration.*

The ultimate dream in the design of an intelligent building is to integrate the four operating areas into one single computerized system. All the hardware and software would be furnished by a single supplier who would use compatible equipment and common CPUs and trunk wiring. The Architecture of Latest Building Automation System (BAS) is illustrated in Fig. 8.

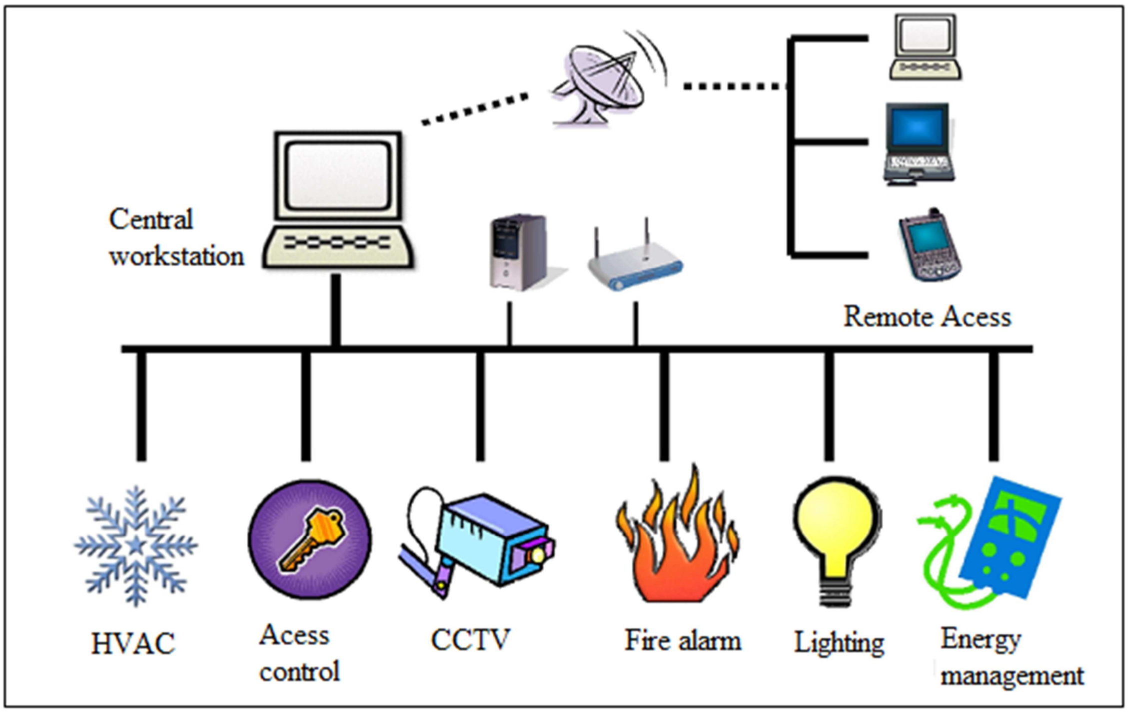


***Figure 8.*** *Basic Architecture of Latest Building Automation System (BAS).*

The process of building of smart building with intelligent solutions initiated from early Nineties gradually and the growth phase took high pace from 2009 onwards. With advent of new smart materials, it is presumed that building of smart building with intelligent solutions will be at its high peak for the estimated period of 2016 – 2025, beyond which, it is presumed that development of building of smart building with intelligent solutions will be completely materialized as illustrated in Fig. 9 [19].

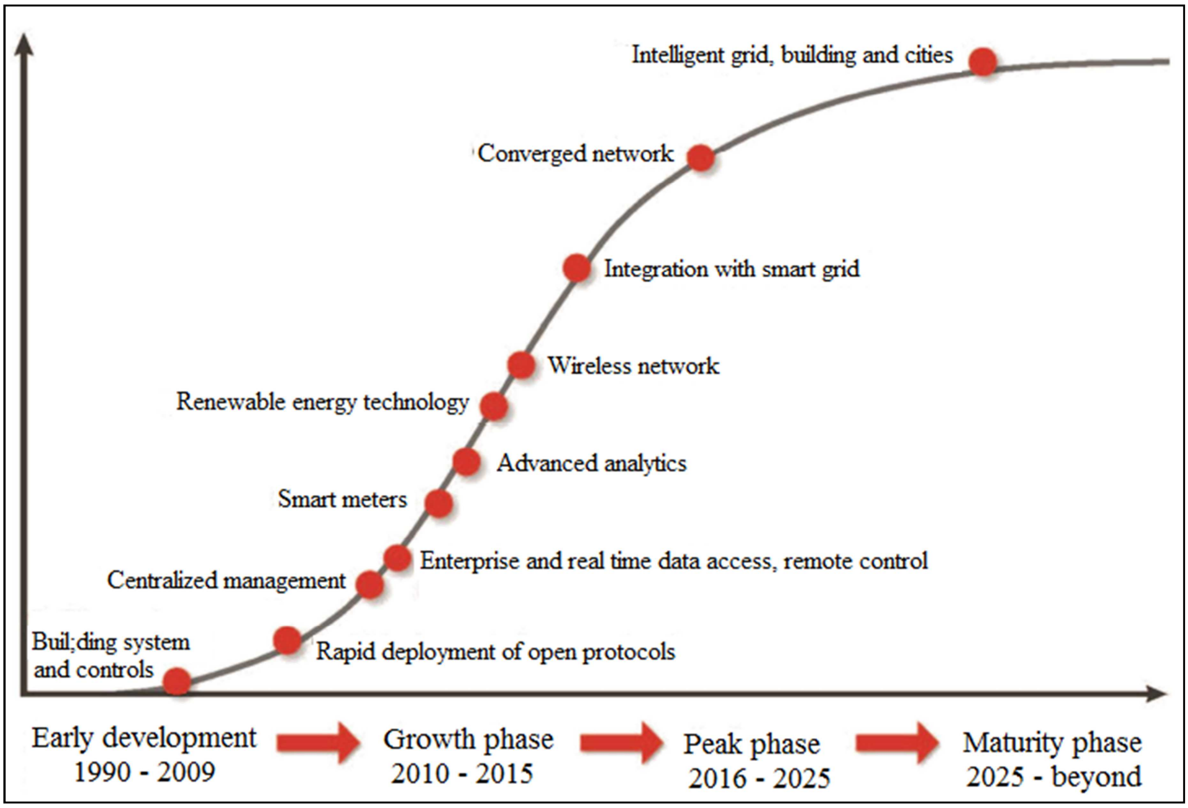


***Figure 9.*** *Development process of building of smart building with intelligent solutions - intelligent building solutions market life cycle analysis.*

### 6.3. Smart Bridges

The potential combination of smart materials and sound engineering knowledge always results in the development of smart structures such as smart bridges. The use of smart materials permit the construction of smart bridges with a wider span to avoid the increased susceptibility to vibrations caused by ambient factors such as wind, rain or traffic. The critical deterioration of transportation infrastructure has put pressures on designers to think for new methods of rehabilitation and repair of bridges across the World. Thus, there has been a new trend in civil engineering called “smart structures”, incorporating sensors in some of the most advanced building materials [20-21]. The designers would prefer to install smart structures and to develop remote systems that would allow monitoring by centrally located smart systems rather than conventional process. Highly sensitive fibre optics is used as sensors, which respond to a change in intensity, phase, frequency, polarization, wavelength or mode. The application of smart materials for bridges provides the following benefits:

a) Less maintenance
b) Real time monitoring of the response of the structure.
c) Monitoring the performance of the new advanced composite materials.

The performance of advanced composite materials can be compared in case of conventional girders in the bridges. Fig. 10 presents, in a schematic way, a section of a smart bridge.

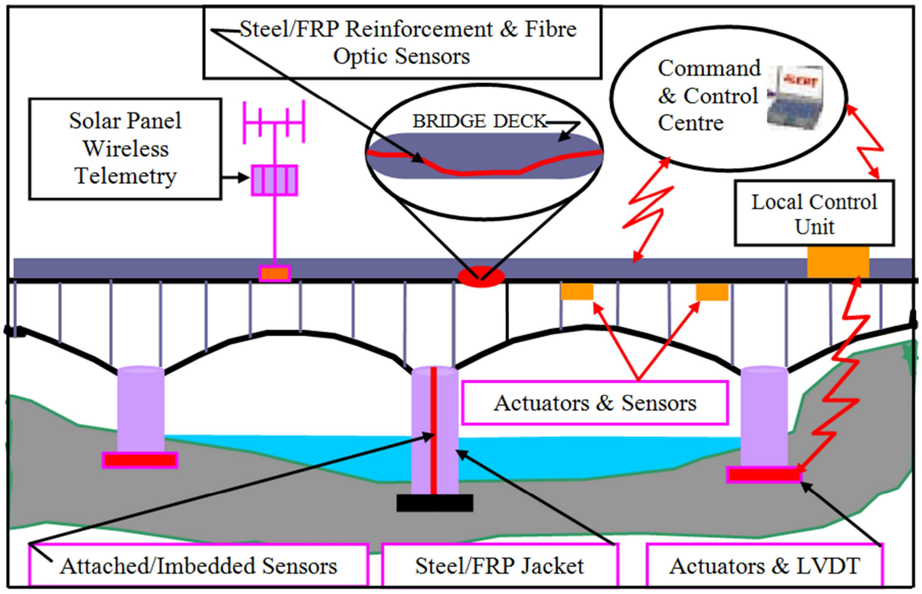


***Figure 10.*** *A Schematic View of a Smart Bridge.*

## 7. General Requirements and Technologies Prospects

For the development of smart materials to be used the construction of smart structure, there is a dire need for novel technologies in the field of science and technology. Researchers and designers are working together to establish need based applications of smart materials and structures. Table 1 summarizes these inter-relationships.

***Table 1.*** *Smart Systems for Engineering Applications.*

| GENERAL REQUIREMENTS | SMART TECHNOLOGIES PROSPECTS |
|---|---|
| 1. Sustainable infrastructures | 1. Smart materials and devices |
| 2. High alert security system | 2. Smart actuation materials and devices |
| 3. Fully integrated building system. | 3. Smart control devices and techniques |
| 4. Health and integrity monitoring system | 4. Smart self- diagnostic devices |

## 8. The Future Scope of Smart Materials

The essence of smart materials is not upto the mark even the smart technologies are under development. Hence, there is dire need for novel aspects of nanotechnology and the newly developing science and technology to cater the needs for future development. The technological benefits of such systems have begun to be identified and, demonstrators are under construction for a wide range of applications from space and aerospace, to civil engineering and domestic products. The technology of smart materials is an interdisciplinary field encompassing the basic sciences, the applied sciences and engineering fields.

## 9. Conclusions

Based on the brief review of this paper, it is concluded that:

1. Smart materials are not only useful but also cost effective as compared to conventional materials for both new and existing constructions.
2. The potential future benefits of smart materials, structures and systems would prove amazing in their scope.
3. Smart technology and smart materials gives promise of optimum responses to highly complex problems.
4. Smart materials provide enhanced preventative maintenance of systems and thus better performance of their functions.
5. The smart structure techniques in conjunction with use of smart materials revolutionize in monitoring the safety and serviceability of engineering structure, structural health monitoring of vital civil engineering structures like bridges, buildings, pavements etc.

Thus, understanding the behavior of any smart material is the ultimate objective of research in the field smart technology.

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