Smart Materials in Smart Structural Systems

Murad Al Qurishee$^1$ & Dr. Ignatius Fomunung$^2$

$^1$Graduate Teaching Assistant, Department of Civil and Chemical Engineering, University of Tennessee at Chattanooga; $^2$Professor, Department of Civil and Chemical Engineering, University of Tennessee at Chattanooga

**Abstract:** Smart materials respond to the change of environment and stimuli (temperature, pressure, electric field, magnetic field etc.) and activate their functions according to the change. To minimize the deterioration of infrastructure, smart materials are one of the best tools. This paper reviews research into the application of six important smart materials—piezoelectric materials, fiber Bragg grating, magnetorheological (MR) fluid, carbon nanotubes, shape memory alloy, and rubber bearing in infrastructural management—by focusing on the literature review, basic useful characteristics and basic information collection of smart materials. Among them the study focuses on the introduction of smart materials, special advantageous characteristics and their application on vibration control, seismic control, structural health monitoring, measuring cracking, corrosion, strains, and so on of the structures.

**Keywords:** piezoelectric materials, fiber Bragg grating, magnetorheological (MR) fluid, carbon nanotubes, shape memory alloy, and rubber bearing

1. Introduction

A conventional structural system, which is designed for a set of intended functions under loads, cannot successfully develop its ability against uncertainties in load and force amplitudes due to external disturbances and the environment unless a large safety factor is provided. Because of the seismic requirement, the old structure’s safety level is inferior to newly constructed structures. To resist vulnerability, the traditional method is to increase the gross section of column, beam, shear wall, and other elements of the structure, which is costly as well as increases the dead load of the structure. In response to the changes in external disturbance and environments, Smart Structural Systems can automatically adjust structural characteristics toward structural safety, serviceability, and the extension of service life [1]. This type of system also offers vibration reduction on structure, seismic control, health inspection of the structure, measurement of crack and so on. This study focuses on some important smart materials such as piezoelectric materials, fiber Bragg grating, magnetorheological (MR) fluid, carbon nanotubes, shape memory alloy and rubber bearing in infrastructural management.

For beams, trusses, steel frames, and cable-stayed bridges vibration are a prime concern which can be minimized by using Piezoceramic patch actuators [2].

The relative low installation cost, remote sensing, ease of installation, non-corrosive and lower maintenance cost of FBG sensor makes them popular and acceptable for measuring vibration and seismic response structures, long term structural health monitoring, short-term condition assessment of structures, measuring internal strain in a dam, and traffic loading assessment on bridges over the last few years. With an annual growth rate of 15% to 25%, the total value of devices and instrumentation of FGB sensors is around $100M USD at present [3].

Magnetorheological fluid dampers provide a new level of technology in earthquake and wind engineering application for vibration control of the structure. These devices gain popularity because of their mechanical simplicity, high dynamic range, low power requirements, large force capacity, and robustness [4].

Carbon nanotubes have opened the door for new smart and advanced sensing materials for continuous health monitoring systems that could detect damages, stains, and corrosions in large complex concrete structures without any wire. A carbon nanotube networks help to make critical decisions regarding operation, maintenance and repairs of any structure by embedding wireless cement–carbon nanotube sensors into concrete beams and subjected to monotonic and cyclic loading to evaluate the effect of damage on that structure [5].

Shape memory alloys are special materials which have numerous civil engineering applications due to their shape memory effect, super elasticity, martensite damping and variable stiffness [6]. It is observed that SMA can effectively resist seismic forces in bridges, buildings or other important architectural heritages than conventional seismic resistant materials. It can be used in beam–column, and column–foundation bolted joints, steel bracing, pretensioning and post-tensioning of concrete beams, restrainers of hinge displacement in bridges and so on [7].

In this paper, structural control devices are discussed focusing on their application to vibration...
control, seismic control, structural health monitoring, measuring cracking, corrosion, strains, and so on of the structures and recommend some future directions to prevent structural damages.

2. Literature review

Smart materials can change their properties (shape, stiffness, velocity) under the influence of electric field, magnetic field or temperature change. The following types of smart materials are discussed in this chapter: fiber bragg grating (FBG), magnetorheological (MR) fluids, piezoelectric materials, carbon nanotubes, shape memory alloys, and rubber bearing [8]. In this chapter, much effort has been made to discuss the use of smart materials in infrastructural management.

2.1. Fiber Bragg Grating (FBG)

2.1.1. Advantageous characteristics

Due to variation in temperature and strains, a fiber Bragg grating (FBG) reflects a particular wavelength of light and transmits all others by making an intermittent variation in the refractive index of the fiber core.

The traditional sensing technologies such as vibrating wire strain gauges, piezoelectric accelerometers and electrical resistance sensors for structural health monitoring (SHM) require many cables. These cables suffer from electromagnetic interference (EMI) for long distance monitoring [9]. On the other hand, FBG sensors offer the following advantages over traditional sensors and the advantages are: immune to electromagnetic interference, lightweight, small in size, easy to install, corrosion resistant, durable and with minimum wiring many sensors can be installed on the structure [10]. It has excellent stability and durability compared with conventional technology. FBG sensor is sensitive to temperature, strain, and pressure [11].

2.1.2. Application in Civil Engineering

Beddington Trail Bridge in Calgary (Alberta, Canada, 1993) was the first carbon fiber composite prestressing bridge in the world, which is three-lane two-span skew bridge and consists of 26 precast prestressed girders with three types of prestressing tendon (steel and two types of carbon fiber composite). In this bridge structure, an array of fiber optic intra-core Bragg grating sensors was attached to monitor the changes in the internal strain that take place over an extended period as shown in Fig 1. The internal strain was also measured with the same set of sensors from both static and dynamic loading of the bridge with a 21ton truck. With such a strain-sensor system, the observation of traffic usage, long-term characteristics of the tendon/concrete bond and the relaxation behavior, extreme load events and the load history of structures, which is useful in determining bridge designs, comparing actual loading with the loads used in the design and specified in bridge design codes, may prove to be helpful for diagnostics and assessments regarding bridge maintenance [12].

The University of Toronto Institute for Aerospace Studies applied intra-core grating sensors in a carbon fiber reinforced polymer (CFRP) prestressed concrete girder and observed that the fiber sensors survived strains of greater than 8000 (με) and there was no change in either center wavelength or spectral content for 2000 (με) over 320,000 cycles [13].

![Figure 1: Bragg grating laser sensor locations in the Beddington Trail Bridge](image)

Hong Kong’s landmark Tsing Ma bridge (TMB) is the world longest (1377 m) suspension bridge that carries both railway and regular road traffic. To investigate the feasibility of using the developed FBG sensors for structural health monitoring, via monitoring the strain of various parts of the TMB under both the railway and highway loads as well as comparing the FBG sensors’ performance with the conventional structural health monitoring system — Wind and Structural Health Monitoring System (WASHMS) that has been operating at TMB since the bridge’s commissioning in May 1997, 40 FBG sensors divided into three arrays were installed on the hanger cable, rocker bearing and truss girders (shown in Fig. 2) of the TMB. The experimental results using FBG sensor and the results acquired by WASHMS were matched excellently [15].

![a) b) c)](image)
2.2. Magnetorheological (MR) fluid

2.2.1. Advantageous characteristics

A magnetorheological shock absorber damper is filled with magnetorheological (MR) fluid, which changes its rheological characteristics in the presence of an electromagnetic field [16]. When MR fluid exposes to a magnetic field, it has the reversible capability to change from a free-flowing, linear viscous fluid to a semi-solid in milliseconds [17], which allows the damping characteristics of the shock absorber to be continuously controlled by varying the power of the electromagnet as shown in Fig. 3. A typical MR fluid consists of 20–40% by volume of iron particles, e.g. carbonyl iron, suspended in a carrier liquid such as mineral oil, synthetic oil, water or a glycol. Iron particles MR fluids have a yield strength of 50–100 kPa for an applied magnetic field of 150–250 kA/m [17].

![Figure 3: Change of free-flowing MR fluid to semi-solid state.](image)

2.2.2. Application in civil engineering

The Cape Girardeau, Missouri, bridge (shown in Fig. 4) was the ASCE first generation benchmark control problem for a seismically excited cable-stayed bridge in which a total of 24 MR fluid dampers were installed to investigate the efficacy of the MR fluid dampers using semi-active control strategy. The arrangement of the MR fluid dampers was four between the deck and pier 2, eight between the deck and pier 3, eight between the deck and bent 1, and four between the deck and pier 4. In this investigation, the modified Bouc-Wen model was considered for the dynamic model of MR fluid damper and a clipped-optimal control algorithm was used for determining the control action for each MR fluid damper. The results of the investigation were that MR dampers are one of the excellent seismic control devices for the cable-stayed bridge [18, 19].

![Figure 4: Schematic of the Cape Girardeau Bridge](image)

2.2. Piezoelectric materials

2.3.1. Advantageous characteristics

Piezoelectric materials can be used in structures to suppress vibration. These materials are lightweight, low-cost, and easy-to-implement for passive and active control of structural vibration. They also offer the sensing and actuation capabilities that can be utilized in vibration control [8].
2.3.2. Operational principle

When a mechanical stress (the usually ambient vibration of the structure) is applied, piezoelectric materials convert the vibration energy into electric energy and vice-versa. These materials can also be used as a method of energy harvesting [23].

2.3.3. Application in Civil Engineering

There are several forms of Piezoceramic materials such as stack actuators, patch actuators, flexible patch actuators, and Macro-Fiber Composite actuators. Stack piezoceramic actuators commonly used in civil engineering, which have many advantages, such as high energy density, compared to other active materials [8, 24].

Piezoceramic patch actuators can be used for the vibration control of cantilever structure [2]. Song et al. (2007) did a multimodal vibration control experiment on an Aluminum cantilever beam which had very low damping characteristics and exhibits significant vibrations when excited, and found a good amount of vibration suppression shown in Fig.5 by placing the piezoceramic patches at the end of the cantilever beam [25]. Vibration control of a flexible structure using linearized piezoceramic actuators showed that without the application of any vibration control on the beam, it takes about 21.5 seconds to damp out to zero when the tip of the beam is held off the balance position 60 mm, whereas with piezoceramic actuators it takes 3.4 seconds to damp out all of the vibration [2].

Figure 5: Vibration control scenario with and without piezoelectric materials [25]

Another application of piezoceramic materials is seismic control of building structures. Li et al. [26] developed a numerically simulated three-story building to demonstrate the effectiveness of piezoelectric friction damper for vibration reduction during a seismic event. For this simulation, the used El Centro earthquake excitation and observed that on the second and third story the reduction ratios of the relative acceleration were 59.7% and 61.1% respectively. On the first, second and third story the reduction ratios of the inter-story drift were 86.1%, 70.0%, and 64.5%, respectively.

In cable-stayed bridge, cables are prone to vibrate due to tower/pylon vibration, the deck motions or wind and traffic induced vibrations. Applying active vibration control to a cable-stayed, 80% of the root mean square responses of the bridge can be reduced [27, 28]. Irvine [29-32] did several experiments on the cable-stayed bridge.

It can use as active vibration control in truss and the experimental results showed that there is about 14.8 dB noise reduction [33].

2.4. Carbon nanotubes

2.4.1. Characteristics of carbon nanotubes

In terms of tensile strength and elastic modulus respectively, carbon nanotubes are the strongest and stiffest materials in the world. The range of Young’s Modulus and tensile strength of single wall carbon nanotube (SWNT) are 1 to 5 TPa & 13-53 GPa respectively. The length-to-diameter ratio of the carbon nanotubes is up to 132,000,000:1 due to exceptional strength and stiffness [34].

2.4.2. Application in civil engineering

A Carbon nanotube neural system for structural health monitoring is a network of a long carbon nanotube neurons which can detect damages, stains, and corrosions in large complex structures without the need for actuators and complex wave propagation analyses by using biomimetic signal processing that minimizes the number of channels of data acquisition needed to detect damage. This nanotube neural system has some advantages over other SHM methods such as the low cost for health monitoring, easy to apply on the surface of structures, no stress concentration, no piezoelectrics, and no storage of high-frequency waveforms [35].

For strain/stress, cracking, delamination and other damages detection, carbon nanotube based self-sensing concrete was used at the Minnesota Road Research Facility (MnROAD) of the Minnesota Department of Transportation, the USA as shown in Fig. 6. In this road test, two self-sensing CNT concrete sensors, a pre-cast sensor, and a cast-in-place sensor were integrated into the concrete test section. After passing MnROAD 5-axle semi-trailer tractor truck and a van over the self-sensing pavement, they observed that the voltage signals of the CNT concrete sensors and those of the strain gauges indicate that generally the CNT concrete sensors have higher detection accuracy than the strain gauges. It has capability for detecting
strain/stress, cracking, delamination and other damages of the pavement [36].

An experimental study of bituminous binder modified by carbon nanotube indicates that when a great amount of CNT (1%) is added to the base binder, the viscosity of the binder gains above 100 and 200%, respectively at 165 and 135°C and significantly increases the stiffness and the elasticity of the base bitumen at low frequencies and high temperatures, indicating an enhancement of the rutting resistance potential [37]. On the other hand, another study related to fatigue properties of bituminous binders reinforced with carbon nanotubes concluded that at 10°C, blends containing 0.5% CNTs exhibit a greater fatigue resistance rather than those with a higher CNTs dosage (1%) [38].

2.5. Shape Memory Alloy (SMA)

2.5.1. Classification of SMA

Shape memory alloy is a special type of alloy that can recover deformation when they are heated above a certain temperature and it has high temperature phase called Austenite and low temperature phase called Martensite with three different crystal structures (i.e. twinned martensite, detwinned martensite, and austenite). If load is applied in the austenite phase of SMA, it will transform to the martensite phase above a critical stress, proportional to the temperatures and upon continued loading, the twinned martensite will begin to detwin, allowing the material to undergo large deformations. Once the stress is released, the martensite transforms back to austenite, and the material recovers its original shape [39] as shown in Fig. 7.

2.5.2. Advantageous characteristics

SMAs have high strength, good elasticity, high power/weight ratio, light weight, shape memory, and the ability to dissipate significant energy through repeated cycling without significant degradation or permanent deformation [40]. The yield strength of shape-memory alloys is lower than that of conventional steel, but some compositions have a higher yield strength than plastic or aluminum, for example, the yield stress for nickel-titanium (NiTi) can reach 500 MPa. But due to high manufacturing cost, usually, SMAs used where super elastic properties are needed.

2.5.3. Application in Civil Engineering

An experimental study on an analytic bridge (three spans, four columns, and 11 girders on each span as shown in Fig. 8) retrofitted with shape memory alloys to reduce the seismic vulnerability of bridge exhibited that for the 0.70 g PGA 1940 El Centro (N-S) ground motion, the SMA restrainers reduce the maximum relative displacement to 49.0 mm, a reduction of 42% of the original displacement and for the 0.82 g the JMA Kobe Record (1995 Kobe Earthquake), the displacement reduction with the SMA restrainers is 49.9 mm, represents a 63% reduction in the relative displacement at the abutment. Because of their super elastic properties and high energy dispassion, SMA restrainers reduce relative hinge displacements at the abutment much more effectively than conventional steel cable restrainers [40].
Figure 8: Configuration of shape memory alloy restrainer bar used in multi-span simply supported bridge at abutments and intermediate piers [40].

The MANSIDE (Memory Alloys for New Structural Vibration Isolation DEvices) did a shaking table tests on an R/C prototype frames with three different protection systems: non-protected (fixed base) structures, base isolated structures (either with rubber or SMA isolators) and structures endowed with dissipative bracing systems (either with steel or SMA braces). The seismic simulations were performed at the Technical University of Athens using the shaking table facility and the sequence of seismic intensities was: $a/g = 0.08 - 0.16 - 0.24 - 0.36 - 0.48 - 0.60 - 0.78 -1.00$. The experimental outcomes demonstrated the general superior performances of the SMA devices with respect to the conventional devices for base isolation system but for dissipative bracing systems, steel braces provide more safety degree than SMA braces [41].

The world’s first application of shape memory alloy devices (SMADs) for seismic protection of masonry cultural heritage structures (MCUHES) began in Italy in 1996 within the framework of the European Commission-funded ISTECH Project. For the prevention of the force imposed by the reinforcement bar on the masonry walls of Bell Towers (Tall and Slender Buildings) during the earthquake, they used 4 SMADs in series with steel bars, connecting the top to the ground, tensioned to apply pre-stress to the masonry as shown in Fig. 9. They also used SMADs devices in Assisi Basilica tympanum, San Feliciano Cathedral facade, and San Serafino Church for seismic protection. The experimental results showed that the peripheral masonry walls of the church facades and tympanums which were poorly connected at the floor and/or roof level, with the incorporation of the SMAD ties can increase resistance against out-of-plane seismic vibrations of such masonry walls by at least 50% [42].

Shape memory alloys can be used as a primary moment transfer media between the steel beam and column connections. A study on Steel Beam-Column connections using four large diameter NiTi SMA bars showed that the connections exhibited a high level of energy dissipation, large ductility capacity, and no strength degradation after being subjected to cycles up to 4% drift [43].

Figure 9: Anchorages: building top (a) and foundation (b); SMADs before assembling (c); Bell-Tower after rehabilitation (d) [42].

2.6. Rubber Bearing (RB)

Rubber bearing is one of the popular technologies to reduce seismic force on structure, which is made by vulcanization bonding of sheets of the rubber to thin steel reinforcing plates.

2.6.1. Application in Civil Engineering

Comparing with the traditional non-isolated structure, RB can reduce seismic force about $\frac{1}{2}$ to $\frac{1}{8}$ of the one of traditional structure. According to the statistical results of 30 buildings with rubber bearings in China, it can save 3% to 15% of the building isolation cost and over 70–100 years of the safely working life [44]. Fig. 10 shows application of rubber bearing in the first multistory building in China.

Figure 10: The first multistory house building with rubber bearing in China [44]

There are five different rubber bearing isolation system in China such as— basement isolation, story isolation, story isolation, top isolation, and skywalk linking isolation shown in Fig. 11 [44]. Basement isolation is the most common method in china for seismic resistance.
3. Conclusions and Recommendations

This paper reviews research into the application of six important smart materials—fiber Bragg grating, piezoelectric materials, magnetorheological (MR) fluid, carbon nanotubes, shape memory alloy, and rubber bearing in infrastructural management due to their cost-effectiveness, measurement and controlling accuracy on vibration control, seismic control, structural health monitoring, measuring cracking, corrosion, strains, and so on of the structures. Smart Structural Systems have more structural safety, serviceability, and the extension of service life compared to the traditional uncontrolled structure. Moreover, numerous analysis and development efforts are needed to deal with the subsequent problems.

✓ Future research works are needed for understanding the suitability of MR fluid damper control algorithms among clipped-optimal algorithm, Lyapunov algorithm, and the modified Bouc-Wen model.
✓ For bituminous binder modified by the carbon nanotube, the determination of % CNTs blends and mixing temperature are needed more research.
✓ An incremental benefit-cost analysis can be done among the magnetorheological (MR) fluid damper, shape memory alloy and rubber bearing for seismic control of the structure to understand the comparative effectiveness within a limited budget.

4. References


