Chapter 1

Smart Materials for Civil Engineering Applications

Abstract
A review of the emerging field of smart materials and structures, with special emphasis on civil engineering applications is presented. Sensing, actuation, and self-repairing applications are covered. The smart materials used for sensing applications cover optical fibers, piezoelectrics, smart tagged composites, and electro/magnetostrictive materials. The smart materials used for actuation applications include piezoelectric and electrostrictive materials, magnetostrictive materials, and shape memory alloys. The self-repairing materials encompass special varieties of cementitious and polymeric materials. For each smart-materials category, a brief description of the physical principles and theoretical basis is given. Major research results and proof of concept demonstrations are summarily reviewed. The advantages and limitations of each smart materials technology are presented and discussed. The chapter ends, with an overall presentation of the current development status in the smart materials and structures field for civil engineering applications, followed by a brief outline of future research needs.

Keywords
Smart, adaptive, intelligent, optical fibers, fiber optics, Bragg gratings, piezoelectric ceramics, piezoelectrics, smart composites, tagged composites, electrostrictive, magnetostrictive, shape memory alloys, ferroelectric, ferromagnetic, PVDF, self-repairing, induced-strain actuation, vibration control, damage detection, health monitoring, failure prevention, life extension, aging infrastructure.

Introduction
Infrastructure decay is a severe problem faced by many developed countries. A major expense in any rehabilitation program is the high cost of structural inspection. Moreover, due to the uncertainties of structural assessment procedures, minor degradations that can be easily repaired may develop into major damages requiring
major repairs or complete re-construction. To reduce the cost of structural rehabilitation, it is highly desirable to have materials that can provide information on their own condition, or even better, materials with the capability of self-repair.

New structural design concepts also impose new requirements on material behavior. Recently, there have been considerable interests in the use of active control to reduce the vibration and damage of structures subject to dynamic load. To make active control possible, materials with actuating capability need to be developed.

In this chapter, we broadly classified smart materials into the following categories:

(i) sensing materials - materials that can provide information on its current condition or ‘health’.

(ii) actuating materials - materials that can change dimensions under external stimulus (such as heating/cooling or the introduction of an electromagnetic field). When restrained, an actuating force will be provided.

(iii) self-repair materials- materials that can repair themselves, for example, through the automatic healing of cracks.

It should be noted that some materials exhibit more than one of the above properties. It is envisioned that smart materials will be used in combination with conventional materials to construct a smart structural system. This often requires the use of a computer as the ‘brain’ or decision-maker of the smart system. For example, to construct a smart concrete structure, optical fibers can be embedded at various locations to monitor the dynamic strain. After the strain information is analyzed by a computer, a signal will be sent to a power supply, which will then apply an electric field to an electrostrictive actuator attached to the structure. The force provided by the actuator can then reduce the vibration of the structure.

In the following sections, sensing materials will be described first, followed by actuating and self-repair materials. After each type of material is described, the current limitations will be highlighted and major research challenges will be identified.

**Sensing Materials**

*Optical Fibers*

Optical fibers were first developed in the 60’s for telecommunication applications. An optical fiber is a glass fiber with a cylindrical core surrounded by a concentric cladding (Figure 1). The refractive index of the cladding is higher than that of the core. When light is sent into the core at a low angle, total internal reflection takes place and the light is transmitted along the fiber with very little loss. With an optical fiber, signals can be transmitted over very long distances without the need for amplification. To protect the optical fiber against scratches and environmental effects, a coating is always applied onto the fiber during the drawing process. In most cases, the coating is made of a polymer (such as acrylate or polyimide). For special applications, metallic coating such as aluminum or gold are employed.
When an optical fiber deforms due to mechanical or thermal effects, the optical signal will be affected. For example, when a fiber is stretched, light travels a longer distance from one end to the other; there will be a change in the phase of the output signal. When a fiber is bent, some of the light will refract from the core into the cladding and get dissipated. As a result, the intensity of guided light will decrease. In fibers with gratings, light of a particular wavelength is preferably reflected. When the fiber is strained, the reflected wavelength is shifted. These changes in light properties form the basis of fiber optic sensing. By coupling an optical fiber to a structure; monitoring the change in light intensity, phase or wavelength at the output, the structural condition can be verified.

During the last two decades, a great deal of work has been carried out in the development of fiber optic sensors for various measurands including distance, velocity, strain, temperature, cracking, pressure, corrosion, maturity of curing, chemical content as well as intensity of high-level electromagnetic fields. Compared with conventional instruments, advantages of fiber optic sensors include:

(i) low signal loss, thereby being suitable for remote sensing,
(ii) immunity to low-level electromagnetic noises common in sensing applications,
(iii) not vulnerable to damage by lightning, which is important to structures such as bridges or dams,
(iv) small size and light weight; hence unobstructive when installed in a structure,
(v) possibility of multiplexing, i.e., having a number of sensing points along a single fiber,
(vi) feasibility of distributed sensing. Any point along the fiber can act as a sensor. This property is critical for crack sensing in concrete structures.

Fiber optic sensing is now a well-established research field with thousands of papers already published in the literature. It is not possible to provide a complete review of the field in this short chapter. We will therefore focus on several topics of particular interest to civil engineers, namely the sensing of strain, cracking and moisture content. For a more general coverage of fiber optic sensing, especially its application in other areas, the reader can refer to the book by Culshaw (1996), as well as the various proceedings on Smart Structures and Materials published by SPIE.

Strain Sensing with Optical Fiber – Fiber optic strain sensing is most often carried out with interferometric techniques. To explain the technique, it is best to consider the Mach-Zehnder interferometer that consists of two fibers. A light beam is split and
coupled into two separate fibers. One fiber is attached to a structure while the other is left free. At the other end, signals from the two fibers are re-combined and monitored. When the structure is loaded, the length of the attached fiber will change, leading to an increase in optical path for the light. The corresponding phase shift will lead to a periodic variation of light intensity when light signals from the two fibers are re-combined. Each fringe (or complete periodic variation of light intensity) corresponds to a change in length equal to the wavelength of light, which is around one micron. Counting the number of fringes can provide enough resolution for the measurement of relatively large strains. For small strain measurements, feedback loops have to be employed to convert the periodic intensity into a linear variation in voltage output (Ezekiel, 1992).

The Mach-Zehnder interferometer has several disadvantages. Two fibers need to be used at each sensing point. Very tight control of bonded fiber length is required to ensure a consistent gauge length, so the measured length change can be correctly translated into a strain value. Also, when low-cost light sources such as LED are employed, the low coherence length requires close matching of the length of the attached and free fibers. In the instrumentation of large structures, long fiber lengths are required and close length matching can be very difficult.

To overcome the above shortcomings, a Fabry-Perot sensor can be employed. An example of Fabry-Perot sensor (called the extrinsic Fabry-Perot Interferometer, EFPI) is shown in Fig. 2. The sensor consists of two optical fibers with partially mirrored ends held at a distance apart by a small glass tube. When light signal is sent into the fiber, part of it will reflect at the first glass/air interface, while another part will reflect at the second interface. The two reflected signals then interfere with one another. On loading, the air gap will change in dimension, causing a change in the difference in optical path of the two light beams. With this configuration, a single fiber can be used at each sensing point. The gauge length is fixed when the EFPI is manufactured. The distances traveled by the two light beams differ only slightly; are much smaller than the coherence length of any laser. The application of EFPI for strain sensing has been demonstrated in various laboratory and site studies. Masri et al (1994) use EFPI for cyclic strain monitoring in a concrete structure and show that the signal/noise ratio is much better than that of strain foil gauges. Habel (1994, 1995) and co-workers have applied EFPI to strain monitoring of concrete during the curing and service stages, as well as strain monitoring of prestressing tendons in a concrete bridge.

![Figure 2 – The Extrinsic Fabry-Perot Interferometer](image)

The interferometric technique described above measures the change in phase relative to a certain state. If the signal is turned off for some reasons, the reference point will be
lost, as it is impossible to determine the number of fringes the output has gone through during the ‘down’ time. To counter this drawback, Tran et al (1993) developed an absolute extrinsic Fabry-Perot interferometer (AEFPI) which employs white light interferometry to obtain the absolute size of the air gap. The applicability of such a sensor has been demonstrated through the monitoring of strain in a prestressed tendon (de Vries et al, 1995).

Figure 3 – A Large Strain Gauge made of Optical Fiber Loops

For absolute strain measurement, the most direct technique is to measure time for light to travel over a certain distance; how this time value changes as the fiber is strained. Such a technique has been employed by Lou et al (1995) for strain monitoring in a composite jacket for column retrofitting. They developed a sensor that consists of many loops of fiber glued to the structure (Fig. 3). At the two ends of the loops are two optical reflectors. By monitoring the Fresnel reflection from the two reflectors, the total length of fiber in the loops can be calculated from the times at which the reflections reach the detector and the light velocity in the fiber. As the fiber is stretched, the new length and hence the strain can be calculated from the new time values. This method has the advantage of directness and simplicity in data interpretation. Also, one can easily obtain strain at different parts of a structure by looping different portions of the fiber at the appropriate locations. Its major disadvantage is the need of a very short pulse to obtain the required time resolution. This makes the required opto-electronics system very expensive. Also, a long length of fiber is required between the reflectors to provide a high strain resolution. This limits the application of the sensor to the measurement of strain over relatively large gauge lengths.

Figure 4 – Low Coherence Interferometer for Absolute Strain Measurement
Another set-up for absolute strain measurement has been developed by Inaudi et al (1994). The sensing principle, which is based on white-light interferometry, is illustrated in Fig. 4. In this case, the sensor consists of two fibers gripped by a pair of ‘wings’ that can be coupled to a structure. One fiber is tight while the other is loose. On loading, only the tight fiber will be stretched and a light path difference is resulted between the two fibers. The signal demodulator consists of a pair of fibers, one terminating at a fixed mirror and the other terminated in front of a movable mirror. With the set-up in Fig. 4, the photo-diode will register a signal only if the path difference between the fixed and movable mirror is the same as that between the tight and loose fibers. The absolute strain can hence be obtained from the position of the movable mirror. Such a sensor has been applied to the deformation monitoring of concrete bridges (Inaudi et al, 1996) as well as underground excavations (Inaudi et al, 1995).

Recently, there is also considerable interest in the development of absolute strain sensors based on the Bragg grating. A Bragg grating is a periodic variation of refractive index along the length of the fiber. It is normally created by interfering two powerful laser beams shooting onto the side of the fiber. The grating period can be controlled by varying the laser beam angle. When a broad band signal passes through the optical fiber, a wavelength corresponding to the period of index variation will be preferentially reflected. When the fiber is loaded, the index variation period will change, leading to a shift in the reflected wavelength. When strain values are required at more than one point along the fiber, gratings of different periods can be created. The reflected signal will then exhibit a number of peaks corresponding to each grating. By monitoring the shifts of all the peaks, strain at each point can be deduced. Cost-effective systems for the determination of shift at multiple sensing points have been developed separately by Alavie et al (1993) and Kersey et al. (1993). Field trials of multiple point dynamic strain sensing with Bragg gratings have been carried out in Calgary, Canada (Maaskant et al., 1993) and New Mexico (Davis et al., 1996).

![Figure 5](image.png)

**Figure 5 – Principle of Strain Sensing with the Bragg Grating**

In their recent work, Measures (1997) and Volanthen et al (1997) have independently demonstrated the possibility of distributed strain sensing with Bragg sensors. The continuous strain distribution over a grating (as much as 10 cm in length) can be determined. This capability will make possible the accurate measurement of strain gradients in structural components. Examples include stress at the anchorage of prestressing tendons, stress around bolt holes and stress at bonded connections.

*Crack Monitoring with Optical Fibers* – In many structures, failure is preceded by the formation of cracks. For concrete structures, small cracks may not affect structural integrity, but they may allow the penetration of water and salt yielding long term
durability problems. Crack monitoring is therefore an important aspect in the health monitoring of structures.

The early fiber optic crack sensors (Rossi, 1989, Huston et al, 1992) rely on the breakage of a fiber to produce a sudden drop in transmitted optical power (or, alternatively, a sudden increase in reflected power). With a single fiber, it is not possible to monitor crack growth. Hale (1992) designed a sensor with several fibers. Crack propagation perpendicular to the fiber direction can then be monitored, as breakage of each fiber will lead to partial loss of the forward signal. The major disadvantages of these sensors lie in the difficulty in controlling the failure consistency.

To achieve consistency, all fibers need to be coupled to the structure in exactly the same way - a task not easily accomplished on site. In addition, since glass is a brittle material with high material variability, even fibers bonded in the same way may fail under very different strains.

Fiber optic sensors with crack monitoring capability have been developed by Wolff and Messelier (1992), Ansari et al (1993); Voss and Wanser (1994). Wolff and Meisseler's crack sensor (Fig. 6) is an optical fiber sensing system attached to the exterior surface of...
concrete structures for the monitoring of displacement between the points of attachment. If the attachment points are too close, a crack may not pass through the sensing system and if the points are too far apart, sensitivity will be low and it is not possible to distinguish between the presence of one widely opened crack or several narrower ones. The sensor developed by Ansari et al (Fig. 7) is a ‘point’ sensor, which means that it can detect and monitor the opening of a crack only if the crack passes through a small sensor loop 31.75 mm in size. Moreover, in order to provide quantitative information on the crack opening, the crack has to pass exactly through the center of the loop because this is the condition under which the loop is calibrated. Thus, while the sensor is useful in experimental fracture mechanics, where crack location can be controlled, its application to real concrete structures is very limited. Voss and Wanser’s sensor (Fig. 8) also relies on cracking to occur between two points where the fiber is glued onto the structure. For large or small spacing between these two points, this sensor exhibits the corresponding limitations exhibited by the two sensors described above.

A new crack sensing concept that does not require a-priori knowledge of crack location was recently proposed by Leung and co-workers (1997). The sensor principle is illustrated in Fig. 9. While it is not possible to predict exact crack locations, the crack opening direction can be accurately determined from analysis. Once the crack direction is known, an optical fiber can be coupled to the structure in such a way that it is making an angle to the crack. One approach, illustrated in Fig. 9, is to couple a ‘zigzag’ fiber to the structure. For easy installation and proper protection of the sensor, the fiber is first embedded into a polymeric sheet that is then glued to the structure. Light is sent into the fiber from one of its ends; the back-scattered signal (at the same end) is monitored as a function of time.

![Figure 9 – Distributed Crack Sensing Concept proposed by Leung and co-workers](image-url)
This technique of signal monitoring is known as optical time domain reflectometry or OTDR. Before any crack is formed, the plot of signal versus time is essentially flat, showing drops only at the turning points of the zigzag fibers. (Note: these losses are shown for a general case - it is possible to use a small curvature at the turning point to avoid the loss). Once cracking occurs, the optical fiber, which is at an angle to the crack, needs to bend to stay continuous. Bending will cause light loss from the fiber core to the surrounding. As a result, the back-scattered signal will show a sudden drop. Knowing the light velocity inside the fiber, the location of the crack can be calculated from the time at which the loss occurs. Also, from the magnitude of the loss, the crack opening can be deduced if a ‘calibration’ relation is available. Preliminary experimental results have shown that small crack openings (about 0.1 mm) can be detected with the proposed technique. Optimization of sensor design is currently under way to achieve a compromise between sensitivity (increased with loss at each crack) and maximum number of detectable cracks (limited by the total loss budget of the OTDR system).

**Water Detection with Optical Fibers** – The capability to detect water content is useful in many civil engineering applications. For example, leakage from pipelines can be detected. By knowing the water content in soil masses and soil slopes, the load bearing capability and failure probability can be assessed. Also, in applications involving grouting, the sensing of water content can provide information on location of dry spots where the grout fails to reach (Michie et al, 1994).

![Figure 10 – An Optical Fiber Sensor for Water Content](image)

A sensor for moisture detection, developed by Michie et al (1994) is shown schematically in Fig. 10. The sensor consists of a glass fiber reinforced plastic (GFRP) with a layer of hydrogel deposited on the surface. On top of the hydrogel are an optical fiber and a dummy fiber, both tightly held by a helically wound Kevlar thread at 2 mm pitch. As the gel absorbs water and expand, the optical fiber will be pushed onto the thread, resulting in bending and signal loss. By monitoring the loss along the fiber with OTDR, distributed sensing of moisture content can be carried out.

**Advantages and limitations of Fiber Optics Sensors** – The advantages of optical fibers over conventional transducers have already been discussed in section 2.1 and will not be repeated here. At the present, the widespread use of the technology is restricted by a number of limitations. The cost of signal demodulation systems is still high. With advances in optoelectronics; innovative developments of more effective demodulation schemes, the cost can be expected to decrease. While the applicability of many sensing concepts (for strain, cracks, moisture etc) have been successfully demonstrated in the laboratory, there is still little experience with application of optical fiber sensors in large-scale civil structures. The long term durability and stability of the sensing system
in the real world environment is not clear. When multiple sensors are required (which is
the norm for civil structures), the maximum number of sensors that can be economically
multiplexed together needs to be considered. In addition, in a large structure,
information will be required at thousands of points. The development of innovative
distributed sensing techniques is therefore an important area for future research.

Piezoelectric Materials

Piezoelectricity describes the phenomenon of generating an electric charge in a material
when subjecting it to a mechanical stress (direct effect); conversely, generating a
mechanical strain in response to an applied electric field. Piezoelectric properties occur
naturally in some crystalline materials and can be induced in other polycrystalline
materials. The distortion of the crystal domains produces the piezoelectric effect. The
domains may be aligned (poled) by the application of a large, field, usually at high
temperature. Subsequent application of the electric field will produce additive strains in
the local domains, which translate into a global strain in the material. The piezoelectric
effect was discovered in 1880 by Pierre and Jacques Curie. The direct piezoelectric
effect has been used for a long time in sensors such as accelerometers. Use of the
converse effect, however, has until recently been restricted to ultrasonic transducers.
Recent developments in piezo-electric ceramics have spurred the use of piezoelectric
materials in a variety of sensor and actuator applications. Piezoceramics are compact,
have a very good frequency response and can be easily incorporated into structural
systems. Within the linear range, piezoelectric materials produce strains that are
proportional to the applied electric field or voltage. Induced strains in excess of 1000
µstrain (0.1%) have recently been reported. These features make these materials very
attractive for a variety of applications.

Principles of Piezoelectricity and Types of Piezo Materials – There are several
approaches to modeling the constitutive behavior of piezoelectric materials. The first
approach is that taken by material scientists. In this model, the effects of the
microstructure and the chemical composition of the material properties are studied. This
approach is useful in improving the basic electromechanical properties of the
piezoelectric materials; however, the parameters involved in such a model are not in a
form where they can be used directly by structural engineers in structural equations.

The second approach is an electrical one, where an equivalent electrical circuit is
developed for the piezoelectric material. This is useful for representing the effect of the
piezoelectric material on the external electrical circuit. This approach does not deal
directly with the mechanically induced strains, which are the source of control in
structural applications. Nevertheless, this modeling is important to structural control
engineers because it is through this model that the electrical power required to drive the
piezoelectric actuators/sensors bonded to the structure is computed.

The third approach is the thermodynamic approach, which is all encompassing and can
deal with all forms of energy and their inter-conversion. Thermodynamics is concerned
with restrictions on the responses of bodies arising from the energy balance and the
entropy inequality. Without these restrictions, mathematically characterized ideal bodies
may not represent physical bodies and their predicted response may not be real. This approach, although best, can be unnecessarily complicated for use in the solution of typical structural problems.

The electro-mechanical approach is the fourth approach and the one that is the most popular with design engineers. It provides the relationship between the electrical and mechanical variables in a manner that can be incorporated into the existing constitutive relations of typical isotropic or orthotropic structural materials. The details of this approach are presented herein.

For linear piezoelectric materials, the interaction between the electrical and mechanical variables can be described by linear relations of the form. The general constitutive equations of linear piezo-electric material behavior, given by ANSI/IEEE Standard 176-1987, describe a tensorial relation between mechanical and electrical variables (mechanical strain $S_{ij}$, mechanical stress $T_{ij}$, electrical field $E_i$, electrical displacement $D_i$) in the form:

$$S_{ij} = s^0_{ijkl} T_{kl} + g_{kij} D_k$$
$$E_j = -g_{jkl} T_{kl} + \beta^T_{jk} D_k,$$

where $s^0_{ijkl}$ is the mechanical compliance of the material measured at zero electric displacement ($D = 0$), $\beta^T_{jk}$ is the dielectric impermittivity measured at zero mechanical stress ($T = 0$); $g_{kij}$ is the piezoelectric voltage coefficient that couples the electrical and mechanical variables. The second equation reflects the direct piezoelectric effect, while the first equation refers to the converse piezoelectric effect.

Another formulation of these equations outlines the current produced by the piezoelectric effect, i.e.,

$$S_{ij} = s^E_{ijkl} T_{kl} + d_{ij} E_k$$
$$D_j = -d_{jkl} T_{kl} + \varepsilon^T_{jk} E_k,$$

where $s^E_{ijkl}$ is the mechanical compliance of the material measured at zero electric field ($E = 0$), $\varepsilon^T_{jk}$ is the dielectric impermittivity measured at zero mechanical stress ($T = 0$); $d_{ij}$ is the piezoelectric displacement coefficient that couples the electrical and mechanical variables. Again, the second equation reflects the direct piezoelectric effect, while the first equation refers to the converse piezoelectric effect.

The mechanical variables in the foregoing equations are the stress $T_{ij}$ and the strain $S_{ij}$, while the electrical variables are the electric field $E_i$ and the electric displacement $D_i$. The stress and strain are second order tensors, while the electric field and the electric displacement are first order. The superscripts $T$, $D$; $E$ signify that these quantities are measured at zero stress, or zero current, or constant electric field, respectively.
Types of Piezo-Electric Materials

Piezocrystals and Piezoceramics – For a long period, from the discovery of piezoelectricity in 1879 and until W.W.II, the only piezo-electric materials widely used were quartz crystals (SiO₂) and Rochelle salt. The latter is a natural ferroelectric material, that posses an orientable domain structure that aligns under an external electric field and thus enhances its piezoelectric response. The discovery of ferroelectric piezoceramics started in the late 1940's with barium titanate (BaTiO₃). In 1954, lead zirconate titanate (PbZrO₃) with its even stronger piezoelectric effects, started to be produced. Under the commercial name of PZT, this material is one of the most widely used piezoceramics. To date, many PZT formulations exist, the main differentiation being between "soft" and "hard" PZT varieties. Other currently available piezoceramics are lead titanate, lithium niobate; lithium tantalate.

Piezopolymers – Polyvinylidene fluoride (PVDF), also abbreviated PVF₂, is a polymer with strong piezoelectric and pyroelectric properties. In the α phase, PVDF is not polarized and is used as a common electrical insulator among many other applications. To impart the piezoelectric properties, the α phase is converted to the β phase and polarized. Stretching α-phase material produces the β phase and metallization of the surface; the application of a strong electric field provides the permanent polarization for the piezoelectric properties. The flexibility of the PVDF overcomes some of the drawbacks associated with the brittle piezoelectric ceramics. As a sensor, it provides higher voltage/electric field in response to a mechanical stress. Its easy formability, along with this property, makes it superior to ceramics as a sensor. The g-constants, which represent the voltage generated in response to a mechanical stress, are typically 10 to 20 times that of piezoceramics. PVDF film also produces an electric voltage in response to infrared light; the pyroelectric coefficient defines this relationship. The constitutive relations for PVDF can be described as

\[
S_{ij} = s_{ijkl}^E T_{kl} + d_{ijkl} E_k + \alpha_i^E \theta \\
D_j = d_{jkl} T_{kl} + e_{jk}^T E_k + \tilde{D}_m \theta,
\]

where, apart from the notations already described, \( \theta \) is the absolute temperature, \( \alpha_i^E \) is the coefficient of thermal expansion under constant electric field; \( \tilde{D}_j \) is a the electric displacement / temperature coefficient.

Applications of Piezoelectric Materials to Stress Sensing

Piezoelectric materials produce a voltage (open circuit operation), or an electric displacement (close circuit operation) when subjected to mechanical strain. In stress and pressure sensing, the PVDF materials have been found to give a better electrical response then piezoceramics due to the inherent low modulus that results in a large strain under small applied stress. An PVDF sensor is used like a strain gage but does not require a conditioning power supply. The output signal is also comparable to that of an amplified strain gage signal. This high sensitivity is due to the low thickness of the typical PVDF film (1 mil). Because of its good sensor properties (i.e., the high g
constant), light weight, flexibility; toughness, PVDF is used in numerous sensor applications. PVDF is very commonly used in switching applications, where it develops a voltage in response to a pressure (it develops approximately 10 V with finger pressure). Keyboards make use of this property. One surface of the film is completely metallized, whereas the other surface is metallized only in areas corresponding to the keys and their associated signal-detection wires. The film is stretched under the metallic keyboard with recesses at various key locations. The finger pressure bends the film, producing a signal corresponding to the specific key, which is then used to perform appropriate tasks.

PVDF film is also used as for acoustic applications both as sensors and as actuators. It is used in compact microphones, earphones; loudspeakers. Specially shaped PVDF sensors have also been used as modal sensors for sensing the natural modes of vibration of structural elements such as beams, plates and cylinders.

Many surveillance systems make use of the pyroelectric properties of the PVDF sensor. This application typically uses two closely coupled sensors. Much like the ambient-temperature compensation scheme used with strain gauge measurements, only one sensor is exposed to the infrared emissions, whereas both sensors respond equally to other stimuli, such as noise, vibration; global temperature changes. Signals from both sensors are combined to detect the infrared signal alone.

**Applications to Health Monitoring** – The electro-mechanical impedance technique utilizes the direct and the converse electro-mechanical properties of piezoelectric (PZT) materials, allowing for the simultaneous actuation and sensing of the structural response. The variation of the electro-mechanical impedance of a PZT sensor-actuator interrogator intimately bonded to the structure is monitored over a large frequency spectrum in the high kHz frequency band. Figure 11 presents the experimental set-up and the conceptual system diagram for health monitoring a structure using the electro-mechanical impedance approach.

![Diagram](image)

**Figure 11 – Principles of the electro-mechanical impedance technique: (a) Equipment schematic; (b) conceptual diagram of the automated monitoring system.**

Two basic ingredients are essential of this method: an array of piezo-electric PZT sensor-actuators applied to the monitored structure; a high-precision impedance analyzer coupled to a data-acquisition computer. The size of the PZT sensor-actuators is typically
small (less than 0.5 sq. in., 0.01 in. thick), allowing for non-intrusive installation in the monitored structure. The PZT sensor-actuator is excited electrically by high-frequency low-power voltage; its complex electro-mechanical impedance is measured over a given frequency range. Figure 12a shows the frequency response diagrams obtained during a typical laboratory demonstration of the electromechanical impedance technique. Figure 12b presents a typical damage index diagram that distinguishes between damaged and undamaged locations during the health-monitoring process.

![Figure 12](image)

*Figure 12 – Typical damage detection results: (a) impedance signature pattern; (b) damage index comparison (Giurgiutiu and Rogers, 1997a).*

The high resolution of this incipient damage detection technique is ensured through the intimate electro-mechanical coupling between the electrical impedance response of the piezo-electric sensor-actuator affixed to the structure and the local mechanical impedance of the adjacent material present in the structure and in the structural joints. Localization of the sensing area ensures sensitivity of the impedance signature only to damage and/or structural changes in the near-field area of the PZT sensor-actuator. The insensitivity of the methods to far-field changes ensures good rejection of the unwanted far-field information and prevents the method from giving “false alarms” due to changes that are part of the normal structural usage (boundary conditions, mass changes, service loads, etc.)

The E/M impedance technique is still in its infancy. However, its potential for application is very large. Proof-of-concept demonstrations for civil engineering applications include the use in the laboratory monitoring of a model steel bridge joint structure (Aires, Chaudhry; Rogers, 1996); of composite overlays masonry repairs (Quattrone and Berman, 1997); in a full-scale Navy pier composite upgrade (Quattrone and Berman, 1997).

*Advantages and Limitations of Piezoelectric Materials* – Piezoelectric ceramics, e.g., PZT, have a large piezoelectric response, but also possess certain limitations. The most obvious limitations are associated with non-linearity, hysteresis, creep, depoling, electrical breakdown; Curie temperature.

Hysteresis is the phenomenon that occurs when, upon removal of the electric field, a certain mechanical strain remains in the piezoelectric material. The cause of the
hysteresis is the energy dissipation due to internal sliding events in the polycrystalline piezoelectric body. The degree of hysteresis depends on the field level, the cycle time; the material of the piezoelectric actuator. Hysteresis is often measured as a percentage of the total strain; typically in the range 0.1 to 10% (Figure 13). Since the energy dissipated in the hysteresis cycle appears in the form of heat, it is a concern in high frequency operations, where it can lead to excessive temperatures.

-200 0 200 400 600 800 1000
\[ \text{Displacement, } u_{\text{ISA}} (\mu m) \]

-20 0 20 40 60 80 100 120
\[ \text{Applied Voltage, } -V_{\text{in}}, (V) \]

Figure 13 The induced-strain linear displacement vs. applied voltage curve for PI P-245.70 PZT translator (Giurgiutiu and Rogers, 1997).

Creep refers to plastic deformations that take place (under constant loads) over time. In piezoelectric materials, it is the prolonged application of electric field that causes the induced mechanical strain to grow with time. Creep is a concern when a piezoelectric sensor is being subjected to a constant force for a long time, or when a piezoelectric actuator is extensively subjected to high dc voltages. Creep is not a concern under ac operation.

Depoling refers to the situation in which, when a high electric field is applied to the piezoelectric opposite to the poling direction, its piezoelectric properties may degrade or it may get poled in the opposite direction. The field that causes depoling is called a coercive field. It is important to note that a high stress level can also cause depoling. For ac operation, the coercive field limit is higher because the duration of the applied field is shorter. The coercive field limit is generally available from the manufacturer; if not, it can easily be determined through a simple experiment.

Electrical breakdown happens when a strong electric field applied in the poling direction before produces loss of the electrical insulation properties of the material allowing flow of electricity through the body of the piezoelectric or across its edges. Electrical breakdown destroys the piezoelectric properties. The electrical breakdown field is quite high and can typically be twice as much as the coercive field. Arcing can also occur at the edges of a piezoelectric wafer at low field levels, but it should not be confused with
electrical breakdown. This arcing is generally due to the debris left adhering to the edges after cutting. The arcing vaporizes the debris, thereby acting as a self-cleaning action.

Curie temperature is the maximum operating temperature beyond which the material loses all its piezoelectric properties. The operating temperature should generally be much lower than the Curie temperature because at temperatures close to the Curie temperature, depoling is facilitated, aging and creep are accelerated; the maximum safe mechanical stress also decreases. For typical PZT material, this temperature is about 350°C.

**Smart Composites by Tagging**

Passive and active tagging are sensing techniques that involve adding “tagging” particles to materials. Embedded piezoelectric, magnetostrictive, electrostrictive, or ferromagnetic particles can be used to provide inherent information about the in-process or in-service state of adhesives and polymers. Tagging offers the advantage of distributed in-situ sensing, which is not possible with many types of sensors. If the material system is properly designed, the tagging particles will not adversely affect the properties of the host material, as will other types of embedded sensors. Passive techniques involve sensing the distribution of the particles. An example of a passive technique is adding magnetic particles to an adhesive and using an eddy current probe to detect voids in a tagged adhesive bond. Active tagging involves exciting the sensing particles and measuring the response of the host material. Applying an alternating magnetic field to a polymer tagged with magnetic particles and measuring the resulting force would be an example of active tagging. Applications of passive and active tagging techniques include characterization of adhesive bonds, cure monitoring, intelligent processing, nondestructive materials evaluation, damage detection; in-service health monitoring.

A sustained effort to develop tagged composites for in-situ and in-service health monitoring and damage detection is taking place under a CRADA agreement between the Construction Engineering Research Laboratories of the US Army Corps of Engineers and the Composites Institute of the Society of Plastics Industries with the cooperation of several universities.

**Tagging Principles with Electric and/or Magnetic Fields** – Many of the established NDE techniques for crack detection and damage assessment rely on electric and/or magnetic principles. For example, the Magnaflux method applies a magnetic field through a ferromagnetic part of machinery and relies on the flux leakage around an open crack to collect fine powders of magnetic particles and produce a visual indication of the crack location. Another well established NDE method for crack detection relies on the eddy currents induced by a probe traveling above the metallic piece under inspection to create a reflected magnetic field whose phase and amplitude modifies when a crack is present. However, most polymeric matrix composites are not ferromagnetic. Hence, ferromagnetic NDE methods cannot be directly applied. Additionally, with the exception of carbon fiber composites, polymeric composites are not electrically conductive; eddy currents cannot be directly induced in them. These limitations can be
overcome by incorporating in the composites trace quantities of tagging materials that will impart magnetic susceptibility and/or electric conductivity. Of these two alternatives, the latter is less attractive since one of the well praised qualities of the polymeric composites is their insulating nature. Tagging with ferromagnetic particles has been extensively studied (Giurgiutiu, Chen, Lalande, Rogers, Quattrone; Berman, 1996). In a first stage of the research, sample specimens incorporating up to 5% by weight of ferromagnetic tags (magnetite, nickel-zinc ferrite, manganese-zinc ferrite, Lignosite, etc.) were produced by a number of industrial partners. The composite used in these experiments was of fiberglass type, with a selection of resins (polyester, epoxy, vinyl ester, etc.) used in the matrix. These specimens were subjected to two types of NDE processes: (a) eddy current interrogation; (b) electromagnetic excitation of structural vibrations. The eddy currents method was not found very effective in detecting internal defects (delamination) since the presence of ferromagnetic tags did not ensure a path for the eddy currents inside the composite. However, this method was found to be effective in detecting defects in carbon fiber composites which are conductive and thus create a path for the eddy currents to form. The electromagnetic excitation of vibrational response was found effective in producing marked difference in the frequency response spectrum due to the presence of simulated defects (Figure 14).

Further investigations were performed on full-scale composite specimens. Pultruded C-shaped composite ladder rails were produced with ferromagnetic tagging particles incorporated in the resin material. The tagged ladder rails were subjected to contactless electromagnetic excitation. The resulting vibrational response was detected with a laser Doppler velocimeter aimed through a small port in the electromagnet yoke (Figure 15a). Thus, the detection method was, again, contactless. A typical vibrational frequency response, investigated in the kHz range, is shown in Figure 15b. This figure also shows the frequency response curve of a specimen with simulated defects in the form of a central web delamination. The marked difference between the two spectra can be
processed to yield significant information about the structural health and the presence of structural defects.

![Diagram of experimental set-up](image1)

![Frequency response diagrams](image2)

**Figure 15** – Active tagging interrogation of full-scale ferromagnetically tagged smart composite C-rail elements: (a) experimental set-up; (b) frequency response diagrams for control and damaged specimens

Two tagging types were used during these experiments: (a) magnetite and (b) Lignosite. The magnetite tagging gave a better response but decreased somehow the strength properties of the composite, probably due to the roughness and hardness of these particles. The Lignosite tagging blended much better into the resin-fiber material system of the composite, but its overall magnetic response was not as good as that of the magnetite.

**Tagging Principles with UV and Fluorescent Light** – Substances that respond to ultraviolet (UV), fluorescent or infrared (IR) light are commonly used in tagging explosives and other high-security materials. The underlying principle of these tags is that luminescence is created when the material is bombarded with high-energy quanta of electromagnetic waves. The same principle can be applied to structural composites to sense the presence of damage and delaminations.

**Magnetostrictive Particle Tagging** – Magnetostrictive materials present the quasi-piezomagnetic effect, i.e. they create a magnetic field when subjected to mechanical strain. When magnetostrictive particles (e.g., TERFENOL powders) are embedded in a polymeric matrix, they can become in-situ strain and stress sensors. If the tagged matrix is subjected to mechanical stress, a state of strain is realized in the heterogeneous medium made up of the matrix and the TERFENOL tags. Hence, the TERFENOL tags generate a magnetic field that can be measured with a Gaussmeter. If the tagged matrix material is used in a fiber/resin composite system, the recorded magnetic response will reflect the state of stress in the composite. The method could be especially effective in detecting cracks, since the stress and strain at the crack tip can be many times larger that the background stress and strain in the composite material. Thus, a simple reading of the magnetic field could detect regions with increased magnetic flux values that are indicative of the presence of internal cracks.
Work in this area has been performed by Rogers et al (1995), by White and Albers (1996) and White, Albers and Quattrone (1996). Rogers et al showed that the presence of a crack in a TERFENOL-tagged polymeric resin subjected to mechanical stress can be detected with a Gaussmeter. Extensive work on tagging composite materials with magnetostrictive powders has been accomplished by White, Albers and Quattrone (1996). Experiments with TERFENOL powder embedded in polymers and polymer composites were performed.

![Graph](image)

**Figure 16** – Correlation between applied stress and magnetic field in magnetostrictively tagged resin: (a) comparison of measurements made in the thickness and axial directions (White, 1999); (b) repeated tests showing consistent response (Quattrone, Berman, and White, 1998)

The magnitude of stress in TERFENOL-tagged materials could be correlated with the strength of the magnetic field detected on the surface of the material (Figure 16). Thus, areas of high stress or concentrated stress are reflected in the magnetic signature of TERFENOL-tagged materials (Travillion et al., 1999). Experiments with magnetostrictive tagging of glass-fiber reinforced composite beams were demonstrated by Giurgiutiu et al. (1999). These experiments extended the correlation between stress and magnetostrictively induced magnetic field to bending loading of full-scale composite members. Further work on this method is under progress towards field portable NDE equipment.

**Advantages and Limitations** – The main advantage of smart tagged composites lays in the fact that this approach will give composites properties that were otherwise unattainable. For example, a polymeric composite is not magnetic, but a tagged composite can be made to respond to magnetic fields. These added properties extend the possible options for in-situ structural health monitoring and damage detection of this class of materials. One of the main concerns about tagged composites is related to the long term durability of the complete system. Long term durability studies are still to be performed and performance indicators have still to be determined in comparison to more conventional material systems. The other concern is the initial and life-cycle cost of these products. Both installation costs and in-service costs for implementing the monitoring functions need to be considered and assessed. Quattrone and Berman (1998) also see as an important question to be addressed the need for creating the appropriate structure to coordinate the information passage between users, developers and installers of smart composites.
Electro/Magnetostrictive Materials for Vibration Control

Principle of electro/magnetostriction – Electro- and magnetostriction is the property of changing the linear dimension under the effect of an externally applied electric or magnetic field. The electro and magnetostriction effects are quadratic, i.e. they depend on the square of the applied field. For this reason, electro and magnetostriction, in its rough form, is not a bi-directional phenomenon. Under the effect of an external field, an electro/magnetostrictive material will generally expand in the direction of the field lines, irrespective of their sense. Electro/magnetostrictive materials can be made to behave quasi-linearly by applying a bias field. This shifts the operating point such that a non-zero expansion is obtained under zero external signals. A subsequent external signal, which adds (positive) or subtracts (negative) from the bias field, will result in a positive or negative displacement with respect to the bias position.

Electrostrictive Materials – A ferroelectric ceramic with interesting properties is the compound lead-magnesium-niobate, or PMN. This material exhibits a strong electrostrictive effect. Electrostriction involves a nonlinear electromechanical coupling for which the material develops a strain proportional to the square of the polarization. The strain versus applied field curves for electrostrictive material is shown in Figure 17. Electrostrictors exhibit considerable less hysteresis; the phenomenon of depoling does not exist. However, commercially available electrostrictive actuators as internally biased such that reverse polarity of the excitation field is unacceptable.

\[
\text{Figure 17 – Voltage-displacement curve for the EDO Corporation model E300P PMN device (1 mil = 25.4 \mu m).}
\]

For PMN-PT (lead magnesium niobate doped with lead titanate), induced strains of approximately 1200 \(\mu\)strain have been reported. The nonlinear electromechanical coupling of this material can be used to develop transducers with tunable sensitivities. Because the slope of the repeatable electric field-to-strain relationship varies, the transduction sensitivity, whether the ceramic is used as an actuator or a sensor, can be controlled by adjusting the dc-bias electric field about which the electrostrictive
transducer operates. The disadvantage of the nonlinear (quadratic) response is the reduced actuator authority for ac operations. Furthermore, the electromechanical response is frequency dependent and is restricted to a rather small temperature range in which the dielectric permittivity is large. The deformation for low applied electric fields is small.

The constitutive relations for electrostrictive actuators are written similarly to those for piezoelectric actuators but second-order terms are included, e.g.,

\[ S_{ij} = s_{ijkl} T_{kl} + d_{ijkl} E_k + M_{klij} E_k E_l. \]  

(4)

In this equation, the first two terms are the same as those used to describe the piezoelectric constitutive law: Hook’s law and the converse piezoelectric effect. The third term represents the electrostriction effect. The components of \( M_{klij} \) are the electrostrictive coefficients. Equation (4) indicates that electrostriction appears as quadratic addition to the linear piezoelectric effect. In fact, the two effects are separable because the piezoelectric effect is possible only in noncentrosymmetric materials, whereas the electrostrictive effects are not limited by symmetry and are present in all materials. In addition to the direct electrostrictive effect, the converse electrostrictive effect also exists.

**Magnetostrictive Materials** – Magnetostrictive materials expand in the presence of a magnetic field, as their magnetic domains align with the field. The magnetostrictive effect was first discovered in nickel in 1840 and was later found to be present in cobalt, iron; their alloys. However, magnetostriction in these materials was relatively small, on the order of 50 \( \mu \)strain. Strains on the order of \( 10^{-2} \) were observed in the rare-earth elements terbium (Tb) and dysprosium (Dy) at very low temperatures (below 180K). Scientists working with the Ames Laboratory and the Naval Ordnance Laboratory (now the Naval Surface Weapons Center) developed Tb-based compounds, such as the commercially available Terfenol-D (Tb\(_3\)Dy\(_7\)Fe\(_{1.9}\)), which have magnetostriction of up to 2000 \( \mu \)strain at temperatures up to 80\(^\circ\) C and higher.

Magnetostriction is dependent on applied stress. When there is no applied compressive stress, the “jump” in magnetostriction does not occur while, above a certain compressive stress value, magnetostriction decreases. The reason for this unusual behavior is that the applied stress changes the alignment of the magnetic domains. The larger the rotation that occurs, the larger the observed strain. With sufficient compression stress (around 7.6 MPa) and no applied magnetic field, a large percentage of the magnetic domains are oriented perpendicular to the direction of applied stress. When magnetic field is applied, the domains rotate to align with the applied field which is in the direction of the applied stress. Note that as the pre-stress is further increased (e.g., 18.9 MPa), large magnetic fields are required to produce the same strains, since the material performs more mechanical work when pushing against a larger stress.

A simple two-dimensional model to explain magnetostriction in TERFENOL was developed by Clark (1992). In the first stage of magnetostriction, the domains are oriented perpendicular to the applied compressive stress at an initial magnetic field of zero. Note that the material consists of alternating parent and twinned phases. Magnetostriction does not occur until a critical magnetic field is reached, when the
parent phase “jumps” to a new direction and large strains are observed. Magnetostriction continues to increase as the applied field is increased beyond this critical value, as both the parent and twin rotate toward the direction of the applied field. This model accurately predicts the observed magnetostriction values.

The following actuator and sensor equations describe the constitutive behavior of TERFENOL material:

\[
S_{ij} = s_{ijkl}^{E} T_{kl} + d_{kij} H_{k} + M_{klij} H_{k} H_{l}
\]

\[
D_{j} = d_{jkl} T_{kl} + \mu_{jk}^{T} H_{k}
\]

(5)

where, in addition to the already defined variables, \(H_{k}\) is the magnetic field intensity; \(\mu_{jk}^{T}\) is the magnetic permeability under constant stress. Of course, the coefficients \(d_{kij}\) and \(M_{klij}\) are defined in terms of magnetic units. The magnetic field intensity \(H\) in a rod of length \(L\) is related to the current in the surrounding coil (with \(n\) turns per unit length) through the following equation:

\[
H = nI
\]

(6)

*Design of damping systems with these materials* – Piezoelectric, electrostrictive and magnetostrictive materials can be used to produce structural damping. Two mechanisms are available: (a) dissipate energy directly through the active material electromechanical interaction; (b) use the active material to enhance the damping properties of a conventional damping material.

The energy can be dissipated using the electromechanical interaction of the active materials in the following way. The active material is connected to the structure undergoing vibration. The deformation of the active material is made to follow the deformation of the structure. As the structure deforms, the active material takes up the strain and transforms it into an electrical or magnetic field, as appropriate for the active material used. If the material is electroactive (piezoelectric or electrostrictive), the induced electric field is used to drive current into an external resistance thus dissipating the energy through Ohmic heating. If the material is magnetoactive (e.g., magnetostrictive), the resulting magnetic field is transformed into induced current into a coil surrounding the magnetostrictive material. The induced current is passed through a ballast resistance that dissipates the energy through Ohmic heating.

The active material can be used to enhance the damping properties of a conventional damping material through the “constraint layer damping effect”. Conventional vibration damping treatments utilize the dissipation properties of viscoelastic materials that are applied to the structure. As the structure vibrates, the viscoelastic material is cyclically deformed and dissipates energy. The energy dissipation in viscoelastic materials is mainly a shear strain effect. This effect can be enhanced if on top of the damping layer one adds a layer of active material. The active material is made to deform in opposite phase with respect to the base structure. Thus, the damping layer in between the active material and the base structure would be subjected to much larger differential strain than if no active constraint layer were present.


**Advantages and limitations** – The main advantage of electro/magnetostrictive materials over the conventional piezoelectric/magnetic materials is their very low hysteresis. This could be especially beneficial in dynamic applications. The main disadvantage of electro/magnetostrictive materials is their nonlinearity. However, by applying a bias field, quasi-linear behavior around the bias operating point can be obtained.

**Actuating Materials**

The electro- and magnetoactive materials previously described for their sensory applications can also be used for actuating applications. For example, a piezoceramic material can be used as a strain sensor by taking advantage of the direct piezoelectric effect that converts a mechanical action into an electric charge. But the same material can be also used for actuation applications by using the converse piezoelectric effect that converts an electrical field into a mechanical strain. Such solid-state actuators that utilize the strain induced in the active material through electric or magnetic actions to produce an output displacement are called induced-strain actuators.

**Piezoelectric and Electrostrictive Materials**

The basic properties and constitutive relations of piezoelectric and electrostrictive materials have been already discussed in detail. Here, attention is focused on the use of these materials for the construction of induced-strain actuators.  

*The use of piezo-materials as actuators* – An electroactive solid-state actuator consists of a stack of many layers of electroactive material (PZT or PMN) alternatively connected to the positive and negative terminals of a high voltage source (Figure 18). Such a PZT or PMN stack behaves like an electrical capacitor. When activated, the electroactive material expands and produces output displacement. Typical strains for electroactive materials are in the range 750-1200 μm/m.

![Figure 18 Induced strain actuator using a PZT or PMN electroactive stack](image)

The PZT or PMN stacks are constructed by two methods. In the first method, the layers of active material and the electrodes are mechanically assembled and glued together using a structural adhesive. The adhesive modulus (typically, 4-5 GPa) is at least an order of magnitude lower than the modulus of the ceramic (typically, 70-90 GPa). This aspect may lead to a stack stiffness that is significantly lower than the stiffness of the
basic ceramic material. In the second method, the ceramic layers and the electrodes are assembled in the "green" state; then fired together (co-fired) under a high isostatic pressure (HIP process) in the processing oven. This process ensures a much stiffer final product and, hence, a better actuator performance. However, the processing limitations, such as oven and press size, etc., limit the applicability of this process to small size stacks only.

The PZT and PMN stacks are surrounded by a protective polymeric or elastomeric wrapping. Lead wires protrude from the wrapping for electrical connection. Steel washers, one at each end, are also provided for distributing the load into the brittle ceramic material. When mounted in the application structure, these stacks must be handled with specialized knowledge. Protection from accidental impact damage must be provided. Adequate structural support and alignment are needed. Mechanical connection to the application structure must be such that tension stresses are not induced in the stack since the active ceramic material has very low tension strength. Hence, the load applied to the stack must always be compressive and perfectly centered. If tension loading is also expected, adequate pre-stressing must be provided through springs or other means.

**Design of effective piezo actuators** – The design of effective piezo actuators is particularly difficult due to the small displacement generated by these materials. Typical maximum strains are in the range of 0.1% which, for a usual length of 100 mm (≈ 4") becomes a no-load displacement of 0.1 mm (0.001"). However, the forces that can be generated by a piezo actuator can be very large; are only limited by the inherent stiffness and compressive strength of the piezo material; by its effective area. For most practical applications, displacement amplification of the induced strain displacement is employed. The effective design of the displacement amplifier can “make or break” the practical effectiveness of a piezo actuator. Giurgiutiu and Rogers (1996a, 1996b) performed extensive studies of the effective design of displacement amplified induced-strain actuators and showed that the most important parameter that needs to be optimized during such a design is the energy extraction coefficient defined as the ratio between the effective mechanical energy delivered by the actuator and the maximum possible energy that can be delivered by the actuator in the stiffness-match condition. (The stiffness match condition is the situation in which the internal stiffness of the actuator equals the external stiffness of the application).

Of extreme significance in the design of an effective induced-strain actuator is the amount of energy available for performing external mechanical work. Comparison of the energy density capability of a selection of induced strain actuators commercially available on the open market was performed by Giurgiutiu, Chaudhry and Rogers (1996a) for the static regime and by Giurgiutiu and Rogers (1996b) for the dynamic regime. Absolute energy values and the energy density per unit mass and unit volume were computed and compared. Figure 19 presents such comparison charts for the energy density per unit volume for static (Figure 19a) and dynamic (Figure 19b) operation.

**Applications** – PZT and PMN actuators can be used as linear actuators in a stack configuration (this utilizes the electrostrictive effect parallel to the direction of the applied field) or to induce bending in the bonded structure (this utilizes mechanical strain induced transverse to the direction of the applied field). Bonded electrostrictive
actuators have been used successfully to control the shape of deformable mirrors. In the stack configuration, they have been used for impact dot-matrix printing. Advantages over conventional electromagnetic actuators included order-of-magnitude higher printing speeds, order-or-magnitude lower energy consumption; reduced noise emissions. A tunable ultrasonic medical probe composed of electrostrictors embedded in a polymer has also been developed.

![Diagram of output energy normalized with respect to volume and dynamic energy output normalized with respect to active material volume]

Figure 19 – Specific energy output capabilities of a selection of commercially available induced-strain actuators: (a) static operation; (b) dynamic operation.

Advantages and limitations – This simple analysis shows that very large output power densities can be extracted from induced-strain devices. The practical limitations on the power delivery capabilities of piezo-active materials stem from three directions:
1. The capability of the power supply to deliver the required reactive input power which can be quite large (kVA range).

2. The dissipation of the heat generated in the active material due to internal losses. These losses can be in the range 5%-10% of the nominal reactive input power.

3. The mechanical resonance of the piezo driven system that sets an upper limit on the frequency variation.

Many of the electric-supply difficulties listed above can be avoided by using piezomagnetic devices, such as TERFENOL-D based induced strain actuators.

**Magnetostrictive Materials**

The basic properties and constitutive relations of magnetostrictive materials have already been discussed in detail. Here, the focus will be on the use of these materials for the construction of induced-strain actuators.

**Design of magnetostrictive actuators** – Magnetostrictive materials can be used to produce an effective actuator. Figure 20 shows the typical layout of a magnetostrictive actuator. A magnetoactive solid-state actuator consists of a TERFENOL bar inside an electric coil and enclosed into an annular magnetic armature (Figure 20). End caps ensure that the magnetic circuit is closed. In this arrangement, the magnetic field is strongest in the cylindrical inner region filled by the TERFENOL bar. When the coil is activated, the TERFENOL expands and produces output displacement. The TERFENOL-D bar, the coil; the magnetic armature, assembled between two steel-washers and put inside a protective wrapping, form the basic magnetoactive induced-strain actuator. Prestressing end springs may also be present.

![Figure 20 – Schematic of a magnetostrictive (TERFENOL) solid-state actuator](image)

The TERFENOL material has been shown to be capable of strains up to 2000 µm/m, but with highly nonlinear behavior. Practical strains employed by the manufacturers of TERFENOL actuators are in the quasi-linear behavior range of 750-1000 µm/m. A typical large-power magnetostrictive actuator (ETREMA AA-140J025) is 200 mm long, weighs ≈1 kg and can produce 0.140 mm output displacement.

**Advantages and limitations** – The main advantage of magnetoactive induced-strain actuators over their electroactive counterparts resides in the power supply requirements. The magnetoactive actuator is a current-driven device; hence can operate at voltages
much lower than the electroactive actuators. Since, at present, the low-voltage power supply technology is more developed and cheaper than the high-voltage technology, the use of magnetostrictive actuator is easier and more attractive.

The main limitation of the magnetoactive induced-strain actuators stems from the necessity for additional elements in the actuator construction. While a bare-bones electroactive actuator need not contain anything more than just the active material stack, the bare-bones magnetoactive actuator needs always to include the energizing coil and the magnetic armature. For this fundamental reason, the power density (either per unit volume or per unit mass) of magnetoactive induced-strain actuators will always remain below that of their electroactive counterparts.

Shape Memory Alloys

The first observation of the shape-memory effect (SME) was made in 1932 with gold-cadmium. The phase transformation associated with the shape-memory effect was later discovered in 1938 with brass. It was not until 1962 that Buehler et al. at the Naval Ordnance Laboratory (NOL) discovered a series of nickel-titanium alloys that demonstrated this shape-memory effect. The shape-memory alloy discovered by Buehler et al., later named Nitinol, has been commercially available ever since. Many materials are known to exhibit the shape-memory effect. They include the copper alloy systems of Cu-Zn, Cu-Zn-Al, Cu-Zn-Ga, Cu-Zn-Sn, Cu-Zn-Si, Cu-Al-Ni, Cu-Au-Zn; Cu-Sn, the alloys of Au-Cd, Ni-Al; Fe-Pt; others. The most common of the shape-memory alloys or transformation metals is the Nickel-Titanium alloy, Nitinol.

Physical basis of shape memory and the different types of shape memory materials – The shape-memory effect (SME) can be described as follows: an object in the low-temperature martensitic condition, when plastically deformed under no external stresses, will regain its original (memory) shape when heated. This process is the result of a reverse martensitic transformation that takes place during heating. The martensitic transformation, which is the essence of the response of shape-memory alloys, may be illustrated simply by the change in martensite volume fraction with respect to temperature. The four important transition temperatures are martensite-finish (Mf), martensite-start (Ms), austenite-start (As); austenite-finish (Af).

Nickel-titanium alloys of proper composition exhibit unique mechanical “memory” or restoration force characteristics. The shape-recovery performance of Nitinol is phenomenal. The material can be plastically deformed in its low-temperature martensite phase and then restored to the original configuration or shape by heating it above the characteristic transition temperature (the characteristic temperature can be varied from -50 to 166°C). This unusual behavior is limited to NiTi alloys having near-equiatomic composition. Plastic strains of typically 6 to 8% may be recovered completely be resistively heating the material so as to transform it to its austenite phase. Restraining the material from regaining its memory shape can yield stresses of 700 MPa.

In addition to the special characteristics noted above, shape memory alloys have some other special properties. The change in the Young's modulus of shape-memory alloys is very different from that of conventional metal materials. For most metals, the Young’s
modules decreases as the temperature increases. However, the Young’s modulus of shape-memory alloys increases within the phase transformation temperature range for the heating process. The Young’s modulus of Nitinol increases three to four times from temperatures below $M_f$ to temperatures above $A_f$. Another property of shape-memory alloys that has attracted a great deal of attention is the damping characteristic (i.e., the internal friction characteristics of shape-memory alloys). The damping properties of shape-memory alloys may be exploited for passive and adaptive dynamic control applications. Shape-memory alloys are different from other materials in other aspects too. The influence of the phase transformation on the electrical resistance is one example. An evolution of the internal resistivity of Nitinol with its phase transition and a clear distinction between the heating and cooling process has been observed. Measuring the electrical resistance of shape-memory alloys is often used to determine the phase transition temperatures.

**Constitutive Relations of Shape-Memory Alloys** – The mechanical behavior of shape-memory alloys is closely related to the microscopic martensitic phase transformation; the constitutive relations developed for ordinary materials such as Hook’s law and plastic flow theory are not directly applicable to shape-memory alloys. Therefore, new constitutive relations, which take into consideration the phase transformation behavior of SMA, have been developed. Several constitutive relations have been developed for shape-memory alloys over the last 20 years (Cory, 1978; Muller, 1979; Tanaka and Nagaki, 1982). While each is unique, none of the constitutive relations has a strong experimental justification; each possesses distinct limitations (Liang, 1990). There are two approaches to developing material constitutive relations. One is the macroscopic phenomenological method that requires a significant amount of experimental work; the other is the microscopic or physical method that derives material constitutive relations based on fundamental physical concepts. Combining both approaches takes advantage of each method and yields a more accurate constitutive model capable of predicting and describing the material behaviors of SMA.

**Modeling of SMA with Internal Variables** – Tanaka and his collaborators (1982, 1985, 1988) developed a model based on the concept of the free-energy driving force. Tanaka’s model considers a one-dimensional metallic material of length $L$ that is undergoing either martensitic transformation or its reverse transformation. The state variables for the material are strain, temperature; extent of phase transformation, $\xi$, which is defined as the martensite fraction. The general state variable is defined as

$$\Lambda = (\bar{\varepsilon}, T, \xi)$$  \hspace{1cm} (7)

The Helmholtz free energy is a function of the state variable $\Lambda$. The general constitutive relations can then be derived from the first and second laws of thermodynamics as

$$\bar{\sigma} = \rho_0 \frac{\partial \Phi}{\partial \bar{\varepsilon}} = \sigma(\bar{\varepsilon}, T, \xi)$$  \hspace{1cm} (8)

The stress is a function of the martensite fraction, an internal variable. From the equation above, the rate for the mechanical constitutive equation is obtained as
\[
\bar{\sigma} = \frac{\partial \sigma}{\partial \varepsilon} \dot{\varepsilon} + \frac{\partial \sigma}{\partial T} \dot{T} + \frac{\partial \sigma}{\partial \xi} \dot{\xi} = D \ddot{\varepsilon} + \Theta \ddot{T} + \Omega \ddot{\xi}
\]  
(9)

where D is Young’s modulus, Θ the thermoelastic tensor; Ω the transformation tensor, a metallurgical quantity that represents the change of strain during phase transformation. The material properties derived from thermomechanics are given as

\[
D = \rho_0 \frac{\partial^2 \Phi}{\partial \varepsilon^2}
\]
(10)

\[
\Theta = \rho_0 \frac{\partial^2 \Phi}{\partial \varepsilon \partial T}
\]
(11)

\[
D = \rho_0 \frac{\partial^2 \Phi}{\partial \varepsilon \partial \xi}
\]
(12)

If the expression of free energy is known, the minimization of the free energy may determine the equilibrium states of phases (i.e., the relation of the martensite fraction with the applied stress and temperature can be determined). However, instead of making the effort to find the free-energy expression, the martensite fraction, \(\xi\), is assumed to be an exponential function of stress and temperature based on the study of transformation kinetics in Tanaka’s model. These functions are

\[
\xi_{\text{M}\rightarrow\text{A}} = \exp\left[A_a (T - T_s) + B_a \sigma\right]
\]
(13)

\[
\xi_{\text{A}\rightarrow\text{M}} = 1 - \exp\left[A_m (T - T_s) + B_m \sigma\right]
\]
(14)

where \(A_a, A_m, B_a, B_m\) are material constants in terms of the transition temperatures, \(T_s, T_f, M_s, M_f\).

Based on Tanaka’s work, Liang and Rogers (1990) modified and extended this model to predict and describe quantitatively the behavior of shape-memory alloys. The above equation integrated with respect to time yields the constitutive equation

\[
\sigma - \sigma_0 = D(\varepsilon - \varepsilon_0) + \Theta(T - T_0) + \Omega(\xi - \xi_0)
\]
(15)

A cosine model that better models the phase transformation was proposed

\[
\xi_{\text{A}\rightarrow\text{M}} = \frac{1}{2} \left[\cos a_A (T - T_s) + 1\right]
\]
(16)

\[
\xi_{\text{M}\leftarrow\text{A}} = \frac{1}{2} \left[\cos a_M (T - T_s) + 1\right]
\]
(17)

where the two material constants are determined from

\[
a_A = \frac{\pi}{A_f - A_s}
\]
(18)

\[
a_M = \frac{\pi}{M_s - M_f}
\]
(19)
The three transition temperatures, $M_f, M_s, A_s$, are linearly dependent on the applied stress. To express the influence of stress on the transition temperatures, the following two material constants corresponding to the slope are introduced:

$$C_M = \tan \alpha$$
$$C_A = \tan \beta$$

where $\tan \alpha$ and $\tan \beta$ are slopes. This effect of stress on the martensitic fraction versus temperature equations is introduced as follows:

$$\xi_{A \rightarrow M} = \frac{\xi_{M}}{2} \left\{ \cos \left[ a_A (T - A_s) + b_A \sigma \right] + 1 \right\}$$

$$\xi_{M \leftarrow A} = \frac{1 - \xi_{A}}{2} \left\{ \cos \left[ a_M (T - M_s) + b_M \sigma \right] + 1 \right\} + \frac{1 + \xi_{A}}{2}$$

where the two new material constants are

$$b_A = -\frac{a_A}{C_A}$$
$$b_M = -\frac{a_M}{C_M}$$

The constitutive equation, together with the martensitic volume fraction equations, provides the information necessary to solve all problems involving linear stiffness structures coupled to an SMA actuator.

**Applications of Shape Memory Alloys** – Shape-memory alloys have been used in many fields and applications over the past 30 years. The first major industrial application of a shape-memory alloy was a cryogenic pipefitting device developed by Raychem Corporation in 1969. Perhaps the best known example of this material is the prototype heat engine developed in the mid-1970’s. Because of its biocompatibility and superior resistance to corrosion, Nitinol has been used in the medical field as a bone plate, an artificial joint; in dental applications. The major industrial application for this material has been as force actuators and robot controls (Funakubo, 1987).

Rogers and Robertshaw (1988) suggested the embodiment of SMA fibers into composites (known today as SMA hybrid composites) to adaptively control the performance of the composites or composite structures. The class of the materials referred to as SMA hybrid composites are composite materials with properties that can be changed or internal forces applied to it by activation of the embedded SMA wires (activation refers to changing the phase of the SMA; this is usually done through resistive heating). One of the many possible configurations of SMA hybrid composites is one in which the shape-memory alloy fibers are embedded in a material off the neutral axis on both sides of the structure in antagonistic pairs. SMA fibers can be embedded in a variety of matrix materials, such as graphite-epoxy, glass-epoxy, thermoplastic materials; other moldable or formable materials.

Two active structural modification techniques have been developed for SMA hybrid composites; one is called active properties tuning (APT), another is active strain energy
tuning (ASET). In active properties tuning, the embedded fibers are actuated by resistive heating (i.e., passing an electrical current through the fibers). Once the temperature of the fibers exceeds the transition temperature, the Young’s modulus of the SMA fibers may be increased in a controlled manner from 27 to 82 GPa. Active strain energy tuning uses the same mechanisms as described above for active property tuning but adds another important control parameter, the restoring stress associated with embedded inelastically elongated SMA fiber actuators trying regain their original shape by contracting.

Using either active properties-tuning or active strain energy tuning can result in significant control of the structural response of a composite structure. The difference between the two concepts is that APT changes the structural response by varying the stiffness of the structure alone, while ASET depends primarily on the recovery force of the plastically elongated fibers to change the structural response. Using active strain energy tuning in almost all cases results in more versatility of control than is possible in APT and can give a wide range of deflection, control. The ability of ASET in active vibration and structural acoustic control of SMA hybrid composites has been demonstrated both theoretically and experimentally.

Advantages and limitations of actuating materials – The main advantage of SMA materials is their capability to produce sizable actuation strains in the range of 4% to 6%. This feature makes the construction of demonstration experiments with SMA actuators very simple and accessible. Another advantage of the SMA materials is that they can be easily actuated through thermal effects. Since thermal effects can be readily obtained, e.g. through resistive heating of the SMA wire when an electric current is passed through, the practical realization of SMA based actuators can be easily attained. This feature reveals an outstanding advantage of SMA actuators, i.e. their inherent simplicity.

One main limitation of SMA actuators is their very poor energy conversion efficiency. This is usually due to the engineering of the SMA application. In the usual laboratory demonstrations, most of the heat generated through the passage of the electric current through the SMA wire is dissipated in the environment and does not produce any useful effect in the energy conversion process. For that reason, typical measured values for the energy conversion efficiency of SMA actuators do not exceed a few percent. These values could be certainly improved by proper thermal-flow management. However, this may happen at the expense of the attractive simplicity of the SMA actuators. At best, the energy conversion efficiency might be raise to the level of current thermal engines, which, by far, do not parallel the high efficiency of electric motors.

Self Repairing Materials

Compared to smart sensors and actuators, self-repair materials are in a much earlier stage of development. The only reported studies, from the University of Illinois, have demonstrated the feasibility of self-repair in both cementitious and polymeric materials. The concept of self-repair through the internal release of a chemical was first proposed by Dry (1990, 1991a). For a material to possess self-repair capability, it is necessary to
have (i) a means for internal storage of the repair material (which is usually a polymer or a monomer) (ii) a stimulus to release the chemical; (iii) an approach to harden the chemical or dry out the water (if a monomer is used). Several alternatives have been suggested by Dry. In one approach, chemicals are stored inside hollow fibers. When cracking occurs to break the fiber, the chemical will be released. In another approach, a soft coating is placed around a hollow and porous fiber where the chemical is stored. When the fiber is pulled, surface sliding removes the soft coating, thus releasing the chemical. As an additional alternative, a wax coating can be put around a porous fiber containing monomers. On heating, the wax will melt and the monomer released. Further heating will then result in polymerization.

Experiments have been carried out to demonstrate the concept of self-repair. Wax-coated fibers containing methyl methacrylate were embedded in cementitious specimens. After a two stage heating process (at 50°C and 100°C), the specimens with the fibers show a much lower permeability than control specimens. SEM investigation has reviewed the release of methyl methacrylate into the cement matrix (Dry, 1991a). In another experiment, porous fibers containing calcium nitrite (a corrosion inhibitor) are covered with polyl. These fibers are placed in cementitious specimens that are exposed to salt water. Once the pH in the cementitious environment drops below 11.5, the polyl coating dissolves to release the calcium nitrite. Preliminary experimental results (Dry, 1991b) have indicated the potential of this approach in reducing the corrosion of steel reinforcing bars under high chloride concentrations.

White et al. (1997) from the University of Illinois have performed work on self-repairing composites. The concept of self-repairing composites is based on the inclusion of polymeric microspheres that contain an uncured "healing" compound. When a crack advancing through the composite matrix hits the microsphere, the healing agent is released. It then flows into the crack to bridge the gap. Upon full curing of the released material, the crack is permanently bridged; the composite is considered repaired. They have focused their work on the repair of polyester resins by encapsulating a mixture of styrene, divinylbenzene (DVB), polystyrene and TBC (as inhibitor). Theoretical modeling (Hegeman, 1997) and preliminary experimental work (Jung, 1997) have shown that the microspheres can indeed be ‘opened’ by an advancing crack. Also, the encapsulated material can cure in-situ to bridge the crack.

Advantages and Limitations

The major advantage of self-repair material is to eliminate the need for regular inspection or monitoring, as the material can repair itself once damage occurs. However, the issues of multiple repairs and continuous self-repair capability (e.g., the replenishment of repair material with external supply) need to be studied further. Moreover, for repair mechanisms involving heating, the applications to large structures require additional investigations.
Current Status and Research Needs

The advantages and limitations of each type of smart materials have been summarized under the corresponding sections. As a summary, we can see that the field of smart materials is still in its infancy. For most of the smart materials discussed in this chapter, we have been able to demonstrate their ‘smartness’ and potential for structural applications in the laboratory. For real world applications, many important engineering issues, such as consistency, durability and cost, have not been addressed. Some smart materials have been used in other fields, such as mechanical or aerospace engineering. The direct transfer of such experience to civil engineering is very difficult, because we are under much tighter constraints. Specifically, civil engineers are dealing with large scale and very complex systems, but are often constrained by a limited budget. To promote the use of smart materials in civil engineering, considerable further research and development are required. Since the field of smart materials is so new, its research and development needs are many. A few that we believe to be most imperative include:

1. The development of smart materials with better performance, together with higher durability and reliability
2. The development of new applications that can take full advantage of material smartness
3. The integration of various smart materials, or the combination of smart materials with conventional materials, to form smart material systems
4. The reduction of production costs for smart materials and systems
5. The development of smart materials and concepts applicable to large scale structural applications

Conclusion

In this chapter, we have looked at various materials that exhibit sensing, actuating or self-repair capabilities. For each of these smart materials, the physical principles behind the smartness are explained and practical applications described. The advantages and limitations of each material are also discussed. In summary, one can conclude that the potential of smart materials in structural applications has been clearly demonstrated through laboratory research in many institutions around the world. However, the field is still in its infancy and further research and development is required to establish smart materials as reliable, durable and cost-effective materials for large-scale civil engineering applications.
References

Optical Fiber Sensor


de Vries, M. J.; Bhatia, V.; Claus, R. O.; Murphy, K. A; Tran, T.A. (1995) “Applications of Absolute EFPI Fiber Optic Sensing System for Measurement of Strain in Pre-Tensioned Tendons for Prestressed Concrete”. Smart Systems for Bridges, Structures and Highways, SPIE 2446, 9-15.


Masri, A.; Abdel-Ghaffar, Higazy, Claus and de Vries (1994) “Experimental Study of Embedded Fiber Optic Strain Gauges in Concrete Structures”, *ASCE J. Eng. Mech.*, 120(8), 1696-1717


*Piezoelectric Materials and Actuators*


EDO Corporation, *Piezoelectric Ceramics-Material Specifications, Typical Applications*. Salt Lake City, UT.


*Electrostrictive Materials and Actuators*

AVX Corporation, Electrostrictive Actuators. AVX Corp., Myrtle Beach, SC


*Magnetostrictive Materials and Actuators*


*PVDF*


*Electro-Mechanical Impedance Technique*


**Tagged Smart Composites**

Giurgiutiu, V.; Chen Z.; Lalande, F.; Rogers, C.A.; Quattrone, R. F.; Berman, J. B.(1996) "Passive and Active Tagging of Reinforced Composite Samples for In-


Self-Repairing Smart Composites


Design of Induced-Strain Actuators

Giurgiutiu, V.; Rogers, C.A.; McNeil, S. (1997) "Static and Dynamic Testing of Large-Amplitude Rotary Induced-Strain (LARIS Mk 2) Actuator", *Journal of Intelligent


Shape Memory Alloy


