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ADVANCED COMPOSITES FOR SMART STRUCTURES

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SUMMARY: Many advanced composite materials have been proposed for smart structures. Beside the aramid, glass and carbon fibre reinforced polymer (FRP) used to replace steel bars, strands, wires or tendons in the structures, FRP panels, membranes and textiles are more and more used in all type of structures.

In the last few years, research has been conducted in the area of advanced composites to be used as smart materials for smart structures. Smart structures and materials are defined as systems which have two basic functions: the first is to sense any external stimuli and the second to respond to that stimuli in some appropriate ways in real or near real time. This intelligent health monitoring is very beneficial to aerospace, mechanical or civil structures. The use of advanced composites for reinforcement as well as for sensing and actuating purposes combined with sophisticated data acquisition and monitoring apparatus has been proposed. This paper examines the sensing and actuating functions as an added value to advanced composites to be used in smart structures and evaluates their potential implications in improving the performance of the structure.

KEYWORDS: Smart materials, Adaptive structures, Sensors, Actuators, FRP, Fibre Optics.

DEFINITION

Smart structures trace their origin to a field of research which envisioned devices and materials that could mimic human muscular and nervous systems. The idea is to produce non biological structures that will achieve the optimum functionality observed in biological systems through emulation of their adaptive capabilities and integrated design. By definition, smart structures and materials consist of sensors and actuators that are either embedded in, or attached to a structure, to form an integral part of the structure. The structure or material and its related components form a system that will react in a predicted manner and in a pattern that emulates a biological function. One of the first attempts to use the smart materials technology involved materials biological function. One of the first attempts to use the smart materials technology involved materials constructed to do the work of electromechanical devices. Since then, many types of sensors [1- 2] and actuators [3] have been developed to measure or excite a structure. Fig.1 presents the general requirements, expectations and needs for smart structures in engineering systems.

General Requirements & Expectations:

I. High degree of reliability, efficiency and sustainability not only of the structure but also the whole system.
2. High security of the infrastructures particularly when subjected to extreme and unconventional conditions.
3. Full integration of all the functions of the system.
4. Continuous health & integrity monitoring.
5. Damage detection and self recovery.
1. Intelligent operational management system.

Smart Technologies Prospects:

1. New sensing materials & devices.
2. New actuation materials & devices.
3. New control devices & techniques.
4. Self detection, self diagnostic, self corrective & self controlled functions of smart materials.

Fig.1. Smart Structures in Engineering Systems.

The basic components of any smart structure have been summarized as follow [4]:

1. *Data acquisition*: the aim of this component is to collect the required raw data needed for an appropriate control and monitoring of the structure.
2. *Data transmission*: the function of this part is to forward the raw data to the local control units and/or to the Central Control Centre.
3. *Central Control Centre* or Data processing unit: the purpose of this unit is to analyse the data, reach the appropriate conclusion and determine the specific actions.
4. *Data instructions*: the function of this part is to transmit the decisions and the associated instructions back to the members, and
5. *Controlling devices*: the purpose of this part is to take action by triggering the controlling devices/units.

By its nature, the technology of smart materials and structures is a highly interdisciplinary field encompassing basic sciences such as physics, chemistry, mechanics, computing and electronics as well as applied sciences and engineering such as aeronautics and mechanical engineering. This may explain the slow progress of the applications of smart structures in engineering systems even if the science of smart materials is moving very fast. An insight into smart structures and their applications is given elsewhere [4]. The purpose of this paper is to present and discuss the sensing and actuating functions as an added value to advanced composites to be used in smart structures and evaluates their potential implications in improving the performance of the structure. This is a part of an ongoing work on the use of smart materials for applications in engineering in general and for structures in particular [5].

ADVANCED NEW MATERIALS

For the smart structures of the future, any new material has to fulfill not only the technical and technological requirements but also the economical, environmental and sustainability criteria as well as the sensing and actuating functions as follow:

- The technical properties include: the mechanical characteristics such as plastic flow, fatigue, yield strength, etc. and the behavioural characteristics such as damage tolerance, electric, heat and fire resistance, etc.
- The technological properties encompass manufacturing, forming and welding abilities, thermal processing, waste level, workability, automation and repair capacities, etc.
- The economical criteria are the raw material and production costs, supply, availability, etc.
- The environmental characteristics mean the toxicity, pollution, etc.
- The sustainable development criterion implies reuse and recycling capacities, etc.
- The sensing and actuating functions imply adaptation to the solicitations.

Combining two or more single materials in an attempt to utilize synergistically the best properties of their individual constituents is the ultimate objective of any composite materials. That is why advanced composite materials are very close to satisfy all the above requirements. Their advantages and adaptability to the above design requirements have led to a profusion of new products. There are basically two types: man-made completely tailored composite materials and a combination of single/composite materials or fibre reinforced polymers (FRP).

Man-made tailored composite

The relative ease with which a non metallic particulate material can be introduced into a powder alloy to form a metal matrix composite encourages the belief that a new range of materials offering improved properties at prices that are attractive to industry may become available in the near future. The gains that can be made in terms of specific strength and specific stiffness by incorporating a strong, fibrous material with some high modulus such as boron or silicon into a matrix of aluminium or titanium are considerable. Here are a few examples:

An example from high-tech applications is provided by materials created by mixing a solid with minute spheres of glass, ceramic, or polymer. Manufacturers have pushed the limits of polymer, glass, and other materials by turning them into sturdy foams. Even some metals are getting the same treatment. New material such as syntactic foams use prefabricated and manufactured bubbles that are mechanically combined with a resin to form composite materials. These new foams could be combined with thin panels or outer skins to create laminated composite or sandwich construction.

As mentioned previously, the use of advanced composite materials is due to the recent progress in their design and manufacturing technologies. As a consequence, the integration of a smart system concept with the composite design could potentially result in significant improvement in the performance of these materials. Numerous investigations have recently demonstrated the feasibility of the integrated concept through the use of simple structures. As an application for domestic use, an active vibration reduction in sporting goods includes a new generation of tennis rackets and golf clubs providing less strain on elbows and wrists while diminishing vibration induced inaccuracies. The next generation of stealth applications for the military requiring noise reduction includes silent running ships and extremely quiet aircraft and vehicles. A smart structure for defence purposes is constructed with a patented technique for producing continuous filaments of piezoelectric ceramic fibre to be shaped into complex

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geometries using conventional textile processing. Once the forms are made, the ceramic is processed into dense fibres, and the piezoelectric ceramic fibre form is integrated into the structure. The application of an electric current causes the fibres to bend, shrink or stretch. By timing these movements to counter vibration, noise and/or shaking can be reduced in applications ranging from helicopter rotor blades, to air conditioner fans, to automobile dashboards.

Even if several analyses and numerical models have already been proposed to analyse the integrated materials and structures, a thorough and comprehensive development in theory and numerical methods is still critically needed to allow this technology to deal with complicated and large scaled structures.

Fibre Reinforced Polymer(FRP)

In many structural applications of civil, mechanical, or other engineering, more and more components are designed and produced with composites. There has been an increasing popularity of aramid, glass and carbon reinforced polymer (FRP) to replace steel bars, strands, wires or tendons used in reinforcing and prestressing techniques for the construction, rehabilitation and upgrading of civil engineering works, such as retaining walls, beams and bridges. FRP is used, for the entire project or for an autonomous component of the structure, as the initial reinforcement or to strengthen the existing structure. In recent years, a myriad of FRP composite products has been proposed and each has its particularities, advantages and disadvantages.

Beside the use of FRP as bars, filaments, fibres or tendons, FRP panels, membranes or textiles are used more and more in all types of constructions. Despite the significant advances in the latest manufacturing processes, including automated or hand fabric layups, fibre placement, resin molding, pultrusion, thermoplastic or/and thermoforming, their cost is still high. Their selection as alternative to other materials is only possible because the tradeoffs between the cost on one hand and the weight, handling, transportation and flexibility of various design configurations prior to concept selection are very attractive and economic. In the last decades, this subject has been widely studied and the number of conferences and meetings dealing with this issue, including this meeting, is growing rapidly [6-8].

SENSING FUNCTION

Fibre optic sensors have been the subject of considerable research for the past 20 years with initial applications focussed on military and aerospace uses. More recently, optical fibre cables, attached or embedded with their associated instrumentation within the structure, have been used in real life structures to measure strain, detect corrosion and vibration. Since the discovery of the photosensitivity in optical fibres by Hill *et al* in 1978 and the development of the transverse holographic writing techniques with a UV laser by Metz *et al* in 1989, many improvements have been realised to this technology. If combining the advanced composite materials and fibre optic sensing together is successful in producing a new product with a mechanical, sensing and transmitting characteristics, the already flourishing industry of advanced composites for the construction, rehabilitation and upgrading of engineering works will be even more attractive and particularly cost effective. Only a few attempts have been tried to associate fibre optics with the advanced composite materials [9]. The characteristics, costs, performance, and integrity of fibre optics being summarized elsewhere [4] only their sensing functions are presented here.

Essentially, fibre optic sensors for smart structures duplicate the action of conventional strain gauges. They respond to a change in transmitted light. This change can be in intensity, phase, frequency, polarization, wavelength or mode. There are basically two types of sensors:

1. The most basic type responds to any form of perturbation, such as bending or twisting, that changes the intensity of the transmitted light. Based on intensity modulation, these sensors reflect the losses that occur when any portion of the fibre is strained along its length, and by the same token, measure only the intensity or amplitude of the transmitted light. They also have the advantage of being relatively simple and compatible with multi modes. Spectrometric sensors, on the other hand, operate by relating changes in wavelengths to the degree or amount of strain. They can be used as localized sensors or in a multiplexed setting. They require additional components for detecting the changes in wavelengths, which drives up the cost. On the plus side, such sensors are highly sensitive, can detect minuscule changes and work well, in instances where chemical detection is important.

2. The second type, more sophisticated, is the interferometric type that responds to changes in phase and spectrometry. These phase sensors come in a number of configurations and are highly sensitive to strains. Michelson and Mach-Zehnder types use two fibres, one for sensing and the second as a reference, while the Fabry-Perot sensor employs a single fibre and reflectors. The polymeric sensor is a special class of phase sensor that takes advantage of polarization for its measurement capabilities. The Fabry-Perot and Sagnac sensors rely on interferometry while the Bragg grating exploits spectroscopy. Gratings are modulated refractive index patterns inscribed in the core of the photosensitive optical fibre. In Bragg gratings, light propagating down the length is selectively reflected at the wavelength which satisfies the Bragg condition. Bragg grating sensors work very well but are expansive while Fabry Perot is for now cheaper to build [10].

Wide area sensing exploits a variety of techniques. Multiplexed sensors, such as Bragg grating combined with wavelength division multiplexing and a broadband light source, can be used to scan a large area. Even optical time domain reflectometers can be put to use along with a fibre equipped with partial reflectors spaced along its length.

Finally, fibre optic sensors are either intrinsic or extrinsic. For the intrinsic sensor, the perturbation acts directly on the while the extrinsic rely on some external entity to modulate the fibre.

ACTUATING FUNCTION

Another facet of a smart structure is the actuation. Actuation can be produced by controlling devices such as actuators, pumps, heaters, dampers, etc. A myriad of new materials has been proposed. Table 1 provides the most important characteristics of some adaptive materials that are considered for the actuating function.

The piezoelectric ceramics have excellent frequency response characteristics but still have some limitations on their capability to produce significant force and stroke. The shape memory alloys can produce large amounts of force and strain but are used in low frequency applications because heating and cooling pose significant limitations on their frequency response. Consequently, the current capabilities of these adaptive materials limit somewhat their potential applications but their potential is increasing daily [11-15].

Commercial Designation	Materials	Composition	Principle of Actuation	Strain Capacity	**Frequency Capability**
PVDF	Polymer	Poly vinylidyne Fluoride	Piezoelectric	150 µ	Average
PZT	Ceramic	Lead Zirconate-lead Titanate	Piezoelectric	600 - 1000 µ	High
Samfenol Terfenol	Earth elements with iron	-	Magnetostrictive	1300 - 2000 µ	High with Reduced Amplitude
Nitinol Flexinol	Nickel Titinate	NiTiCu CuAlNi	Shape memory Alloy	3000 - 5000 µ	-

Table 1. Properties of some active materials

EXAMPLE

Bridges and tall buildings are good examples for smart structures. In recent years, the fundamental theories of structural dynamics necessary for the concepts of passive energy dissipation have been studied and explored in details to produce many systems of energy dissipation devices. Some of these devices are installed in a wide variety of structures to resist both wind and seismic loadings: metallic and metal type alloys dampers are used to upgrade the seismic capability of existing structures in high earthquake regions. Other types of dampers utilise the same friction techniques used in the automotive braking systems to dissipate energy. A more recent third approach proposes viscoelastic dampers. In contrast to these solid dampers, fluid type dampers based on liquid motion are also used as vibration absorbers. All the previous dampers or vibration absorbers perform in a self-reliant and passive way [16-18].

Passive control refers to systems that utilize the response of structures to develop the control forces without requiring an external power source for their operation. New concepts for active control to reduce the response of structures to wind, earthquake, blast and other dynamic loadings, have recently been proposed. Active control refers to systems that require a large power source to operate the actuators that supply the control forces, whose magnitudes are determined using feedback from sensors that measure the excitation and/or the response of the structure.

Until now, actuators have not been used to a great extent because of the large forces required to excite a large structure like a building or a bridge. However, this situation is changing. A variable orifice fluid damper has been discussed recently to control the motion of bridges experiencing seismic motion [19-20] and a hydraulic actuator with a controllable orifice was implemented in a single lane model bridge to dissipate the energy induced by vehicle traffic [21]. Semi active control combines the features of active and passive systems, and with variable dampers, they can be very effective in controlling the motion of a structure [22-23].

The smart materials and structures' techniques could certainly improve the performance of the previously described dampers. Many if not all these devices have processors to manage and control their performance. A first level of smartness would be to allow all the dampers of a structure to communicate with each other in such a way to act in coordination. This can be achieved by using some of the FRP reinforcement as fibre optic cables for communication purposes. Until recently, this coordination was theoretically possible but cumbersome, difficult and expensive to enact. Now, with JINI of Sun Microsystems, HART (highway Addressable Remote Transducer), Foundation Fieldbus or any similar process, the technology provides mechanisms that can group easily and cheaply the dampers together into a service network.

A second level of smartness is to use various new enhanced materials such as shape memory alloys, piezoelectric materials, magneto or electro rheological fluids to construct dampers capable to respond in real time when subject to particular solicitations. Thereafter, connect all the dampers together to constitute a smart structure.

Finally, tailoring a structure to suit design requirements while minimizing weight and optimizing other performance variables is still a challenge for design and manufacturing. Usually, the composite materials' behaviour is analysed from the lowest composite level such as the fibre and matrix constituents to the higher level such as the ply and laminates using composite micromechanics and laminates theories. A multilayered composite could also be composed of multiple materials and subjected to a multitude of simultaneous loads. The behaviour of composites is intimately related to the deformation and failure micro mechanisms, including their exact sequence and interaction. These in turn are related to the properties of the constituents (i.e., matrix, fibre, and interface or interphase), as well as processing residual stresses. Although the micro mechanics of stress transfer and fracture have been studied experimentally and analytically by many investigators and the failure mechanisms are known and understood, their relative magnitudes, exact sequence, interactions and quantitative effects on the overall macroscopic behaviour are still a challenge and vary from case to case. For example, failure mechanisms in a multidirectional laminate include matrix cracking, which can be intra laminar or inter laminar, fibre fracture and fibre/matrix debonding. The predominant mechanism in the initiation stage, predicted by first-ply-failure theories, is the formation of intra laminar matrix cracks in the off-axis plies. In many applications, since it is not practical to limit the design to first ply failure, it is critical to understand the entire damage process and the accompanying changes in properties to be able to take advantage of their characteristics [7-8] and control their sensing and actuating functions.

CONCLUSION

If fibre optic sensors and actuators are to be incorporated with the advanced composites materials in the structure to transform it to a smart one, the geometry of the structure and the locations of the sensors/actuators will have a strong impact not only on the manufacturing technique selected but also on the processing of the variables involved, which is not fully addressed yet. This additional constraint will certainly complicate the whole process and require a substantial effort to integrate this new requirement to an already multi disciplinary problem with various disciplines.

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