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Literature Review and Assessment of Nanotechnology for Sensing of Timber Transportation Structures Final Report

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Abstract

There have been recent successful efforts to develop smart structure technology. For the most part, these developments have been developed using currently available, off-the-shelf technologies. Almost simultaneously have been notable fundamental efforts aimed at developing nanotechnologies. Because of the fundamental nature of these efforts, a good understanding of how nanotechnologies might be integrated into smart timber bridge concepts has not existed. The objective of this work was to review the current state-of-the-art and state-of-the-practice of nanotechnology with a specific interest in timber bridge applications. The results of this review indicate the need for more coordination between fundamental researchers and applied researchers. Further, it does not appear that there are any ready-for-implementation nanotechnologies. However, it does appear that several existing, early-stage nanotechnologies could, with appropriate efforts, be further developed with timber applications in mind.

Keywords: wood, bridges, timber, nanotechnology, monitoring, instrumentation, performance, literature

Contents

Introduction 1

Objective and Scope of Work 1

Scholarly Findings 1

Sensors and Carbon Nanotubes 1

Structural Health Monitoring 6

Concluding Remarks 9

Literature Cited 9

Additional References 10

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Literature Review and Assessment of Nanotechnology for Sensing of Timber Transportation Structures Final Report

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Introduction

Recently efforts have been put toward the development of civil structures that have embedded sensors and on-board data processing capabilities, typically termed "smart structures." The fusion of these smart technologies into infrastructures is intended to give bridge owners/managers better and more timely information on how structures are behaving and when they need maintenance. Until the present, most of these efforts have focused on ways to integrate conventional sensors and development of data processing algorithms. Almost simultaneously, fundamental research has occurred on what is generally termed nanotechnology. Nanotechnology can take on many forms but can generally be thought of as very, very small sensors, machines, or devices that are infused within a larger element and/or system. Because most of this research has been of a fundamental nature, a complete document relating nanotechnology to timber structures has never existed. As such, a good understanding of how nanotechnology might complement other smart structure advancements does not exist.

Objective and Scope of Work

The objective of this work was to review the current state-of-the-art and state-of-the-practice of nanotechnology with a specific interest in potential timber bridge applications. To complete this work, the research team performed a general literature review on nanotechnology. Following the collection of the literature, a preliminary review was completed to filter out the most promising information. The most promising literature was then reviewed for its applicability in timber structures.

Scholarly Findings

Sensors and Carbon Nanotubes

In general, the information presented in this section on nanotechnology sensors and carbon nanotubes is quite broad in nature, whereas a subsequent section focuses on a specific, although still general, area of application.

Introduction to Carbon Nanotube and Nanofiber Smart Materials (Kang and others 2006a)

Carbon nanotubes (CNTs) are reported to have good mechanical properties. They are the strongest and most flexible molecular material with a carbon–carbon bond. They also exhibit electrical conductivity or semiconductivity. Last, they have thermal conductivity in the axial direction. These properties make the carbon nanotube an excellent material for sensing and power generation applications.

There are different types of CNT materials: the single-wall carbon nanotube (SWNT), the multiwall carbon nanotube (MWNT), and the carbon nanofibers (CNF). SWNTs have excellent mechanical and electromechanical properties. However, they are difficult to integrate into polymers at high loadings. Because these are single-wall carbon nanotubes, their wall is one atom thick. Generally, the SWNT has a diameter of 1.4 nm and a length that can be greater than 200 nm. The MWNT has multiple walls and generally a diameter of 10 nm or larger, which is an advantage when working and processing the nanotube. MWNTs have good electrochemical properties, are easy to incorporate into polymers, and are moderately priced. The last of the materials that generated from carbon nanotubes are the carbon nanofibers. CNFs have moderate electrochemical properties. The main difference between CNFs and nanotubes is that they are not continuous like the MWNT or the SWNT. These fibers are easier to incorporate into polymers, compared with the SWNT and MWNT, because of their larger size.

There is a potential to develop better actuators with "higher work per cycle…and generate higher mechanical strength." One of the first actuators built with the nanotube/nanofiber technology is known as buckypaper. In very general terms, buckypaper is a thin sheet made from many CNTs.

The properties of CNTs make them promising for sensing applications. Studies of CNTs were first performed using Raman spectroscopy. This technology did not prove to be practical for engineering applications because of its complexity. A different approach was developed using a buckypaper sensor. Buckypaper has a high sensitivity to strain in the "linear bending range." The down side of buckypaper is that slippage between the carbon nanotube bundles affects the strain transfer and degrades the strain sensitivity. For this reason, another material was developed—a composite material sensor. The composite material was developed to improve the slippage between the nanotube bundles. The binding agent used was the polymer polymethyl methacrylate (PMMA). Test results proved that this composite material has a lower sensitivity compared with buckypaper, but has a "linear symmetric strain response in both compression and tension." Another sensor was developed, the long continuous sensor, or the structural neuron. This sensor consists of multiple "neurons" made out of CNT fabricated as long films on the surfaces of composites. These neurons are able to measure strain and the crack propagation in structures to create an artificial neural system (ANS). This ANS can be used in large structure such as "aircrafts, helicopters, and civil infrastructure." One of the most important factors to consider when using the ANS is the cost. The cost of carbon nanotubes can be high, which is why we recommended MWNT over SWNT.

There has been an initiative (Kang and others 2006a) to start the development of "intelligent electronic materials based on a conductive polymer matrix and carbon nanotube." "The sensing capability [of the CNTs] allows the material to monitor its own health while the actuation capability allows it to actively improve the performance of the structure and extend its life." To read the strain response, electrical impendance spectroscopy (EIS) can be used. This development is still under investigation.

Carbon Nanotube Strain Sensor (Kang and others 2006b)

Carbon nanotubes are reported to have great mechanical, electrochemical, and piezoresistive properties. These qualities, in addition to the large surface area, make the nanotube an excellent material for construction of sensors. Raman spectroscopy at the nanoscale has been used to study the strain-sensing capability of the CNTs, but this system is too bulky for sensing applications. The exploration of other uses for CNTs for sensing applications follows.

Buckypaper Strain Sensor—To build the buckypaper, single-walled CNTs (SWNTs) were used. These were dispersed in a dimethyl formamide (DMF) solvent. Then they were poured in a filter paper (P8 filter paper). A Teflon (DuPont, Wilmington, Delaware) casting mold is also a successful alternative. These were vacuum-dried for 12 h at 60 to 70 °C. The buckypaper film was then peeled off.

The testing results of this sensor showed that the SWNT sensor based on buckypaper has high sensitivity to strain. The problem is that it has weak axial van der Waals attraction between the CNT. This causes slippage of the nanotubes in the buckypaper, which results in a degradation of the strain response of the sensor. In a dynamic load test, the strain response wasn't as successful.

SWNT/Polymethyl Methacrylate Composite Sensor

To improve the strain transfer capabilities of the CNT-based strain sensor (buckypaper, specifically), a PMMA composite was used as a binding material for the buckypaper. Construction of the buckypaper with the PMMA is very similar to the one mentioned previously, but the PMMA was added to the suspension of SWNTs in DMF. Then the mixture was then cast in a Teflon mold. It was cured in a vacuum at 120 °C for 12 h.

Test results on this sensor concluded that there was an improvement of the strain transfer across the sensor. The adhesion between the nanotubes was improved, mostly because of the "stronger polymer interfacial bonding." This sensor type had a good response under static and dynamic strain. A disadvantage associated with this type of material is that it has lower sensitivity than buckypaper.

Artificial Neuron Based on a MWNT Strain Sensor

A neural system can be fabricated out of carbon nanotubes. Long films composed of CNTs "connected in parallel with logic circuits" form an artificial neural system. This type of sensor can monitor large areas, especially bridges and buildings. Nanotubes can be placed as neurons. These CNT neurons can detect large strains at distributed points. An advantage of this system is that it can predict the location of cracks, as well as the strain. Also, the installation of the strain sensor system can be proven to be less cumbersome than installing individual strain gauges.

Nanotube Film Based on Single-Wall Carbon Nanotubes for Strain Sensing (Dharap and others 2004)

Carbon nanotubes have good mechanical and electrical properties. The carbon nanotubes in composites are capable of producing high-strength materials with strain sensing capabilities. Carbon nanotube films, also called buckypapers, can be used as actuators. "Results showed that large actuator strains can be achieved by smaller operating voltages compared with ferroelectric and electrostrictive materials." Some researchers have "studied the effect of stress or strain on the Raman-active modes. Recently, researchers have presented results about the Raman shift." The down side about Raman spectroscopy for strain measurement is centered on its bulk. "Carbon nanotube films can be integrated into the material, for example in composites, and can function as sensors and structural material as well. The ability of such films to measure strains on the macro scale is demonstrated by experimental results."

The process of making the buckypaper is as follows:

"… is produced by mixing unpurified SWCNTs from Carbon Nanotechnologies Incorporated (CNI, Houston, Texas) with 0.25 mg/mL–1 N, N-dimethylformamide (DMF) The mixture is filtered by a 0.2 mm Teflon membrane. The film (buckypaper) is peeled from the filter after drying. Then the film is further dried for 24 h under vacuum and heat."

"The carbon nanotube film is attached to a 12 in. × 1.5 in. × 0.25 in. brass specimen having a Young's modulus of 166 GPa. A PVC film is attached, between the carbon nanotube film and the conducting brass specimen, by high strength epoxy for perfect strain transfer and for insulation."

After some testing, a linear relationship was found between the change in voltage from the nanosensor and the strain gauge. One aspect that was not considered and left for future research was the effect of temperature during the experiment. Hone et al. and Bezryadin et al. (Dharap and others 2004) "have observed that the resistance of a carbon nanotube changes with temperature." Results are very encouraging and "indicate the potential of such films for multidirectional and multiple location of strain sensors on the macro scale."

Characterization and Modeling of CNT-Based Actuators (Riemenschneider 2009)

In smart structures, the actuator plays an important role. Actuators induce strain and forces in a system. These are able to change shape and to compensate for vibrations within the system. There are two types of actuators: piezoceramics (PZTs) and shape memory alloys. The difficulty is that these require high voltage and currents, and the materials have a high density. Carbon nanotubes, on the other hand, have a low density of 1.33 $g{\cdot}cm^{-3}$ and require a low voltage if used in actuators. Riemenschneider predicted that actuators made out of CNT can generate stress that are one or two orders of magnitude higher than the current PZTs. So far, the two types of actuators based out of CNT are electrochemical and electromechanical.

For the experimental laboratory work conducted by Riemenschneider (2009) buckypaper was produced at the author's facility. The single-wall carbon nanotubes (SWCNTs) used to create the buckypaper were purchased from a private organization. "This material was synthesized by a process referred to as "CVD" and the purity of this SWCNT batch was denoted by the produces as more than 90% pure. 30 mg of SWCNT material was dispersed in 30 mL 1% solution of sodiumdodecylsulphate (SDS) as a surfactant and then processed by three-step ultrasonication. The dispersion was vacuum-filtered over a polytetrafluoroethylene membrane."

The electrochemical behavior was tested by using cyclic voltammetry, whereas for the electromechanical investigation "the voltage of the minimal displacement U_0 has to be found; this is dependent on the type of reference electrode used." Two types of electrolytes were used for the tests: liquid and solid.

Multi-walled carbon nanotubes were also tested. Riemenschneider found that "displacements are much smaller for multi-walled tubes, just as the capacity of this system is decreased by the same order of magnitude. The reduction of the capacity is caused by the smaller specific surface of the multiwalled tubes."

High-Purity Diamagnetic Single-Wall Carbon Nanotube Buckypaper (Kim and others 2007)

Single-wall nanotubes have unique electrical, thermal, and mechanical properties. However, these valuable characteristics are highly affected by impurities. Various methods used to remove magnetic impurities are chemical treatments, microwave heating, mechanical filtration, and heat treatment. While some of these processes are able to remove the graphitic coating around the ferromagnetic catalyst, they can also destroy the SWNT. "By using isotopically enriched C[arbon], researchers have made SWNT materials from which NMR [nuclear magnetic resonance] signals can be observed after magnetic processing using standard techniques common to biochemical fields." The purification methods currently employed are not sufficient to "achieve the levels of purity necessary for elastic and thermal applications and for the study of standard nonenriched nanotube materials." For this research, a new purification procedure that combines air oxidation and chemical treatments was developed that is able to remove ~99% of ferromagnetic or superparamagnetic impurities.

The carbon nanotubes used to develop the buckypaper were obtained from Carbon Solutions (PII-SWNTs, Carbon Solutions, Inc., Riverside, California). The methods and tests used to measure the "effect of the purification procedure on impurity content" include magnetometry probes, thermogravimetric analysis (TGA), X-ray diffraction, and NMR experiments.

The magnetization studies "confirm that magnetic gradient filtration effectively reduces ferromagnetic impurity content." Also, the purification method used in this research increases "SWNT content relative to pretreated materials and yields clean surfaces suitable for filling experiments" (Kim and others 2007).

Application of MEMS Force Sensors for in situ Mechanical Characterization of Nanoscale Thin Films in SEM and TEM (Haque and Saif 2002)

Mechanical characterization of thin films has become important for uses on microelectronics, micro-electro-mechanical systems (MEMS), and data storage. How reliably these mechanisms function depends on how the thin films respond to the applied stresses. Research has been developed to find tests that can model the behavior of these thin films. The uniaxial tensile test is a test good for gathering information regarding the elastic and plastic regimes. The setback of this test is that when it is applied on a nanoscale thin film, it experiences some difficulties:

- It requires small forces.
- The fabrication of a stress-free specimen is difficult.

- "Gripping and alignment of a nanoscale freestanding specimen is difficult to achieve."

Through experimentation, "an improved device design and a new robust fabrication process for cofabrication of a uniaxial tensile sample and force sensor" was discovered. The experiment equipment consisted of a tensile test chip and a piezo-electric actuator.

Haque and Saif concluded from the experimental work that "…the tensile testing technique is capable of measuring prestress in a specimen, gripping and aligning the specimen automatically, and measuring creep activation energy for thin films." The size did not affect the elastic modulus with an average grain size of 50 nm, but the size effect was observed on the yield strength. "No strain hardening of materials was observed, [but] stress relaxation was observed when small regions of the specimens were exposed to the electron beam."

Carbon Nanotube Memory Devices of High Charge Storage Stability (Cui and others 2002)

Single-walled carbon nanotubes have been found to be attractive in creating molecular electronic devices. Development of the first prototypes for memory devices based on SWNT has begun.

For this research, Carbon Nanotubes (US Research Nanomaterials, Inc., Houston, Texas) were dispersed in aqueous solution and "deposited on a highly Sb-doped silicon wafer with a 100 nm thick thermally grown SiO_2 layer previously surface modified by amino-salinization." "Source and drain contacts (15 nm AuPd without any adhesion layer), separated by ~150 nm, were defined on top of the SWCNTs by electron-beam lithography."

High memory storage devices could be fabricated from SWCNT bundles, "which consisted of a mixture of semiconducting and metallic tubes." This can be done by heating the samples for several hours in air, combined with a method involving a controlled oxygen plasma treatment at room temperature.

The mentioned methods have been proven to be successful. They exhibit a "high storage stability of >12 days at room temperature…the memory devices represent a significant extension of the range of SWCNT applications."

Fabrication of Single-Walled Carbon Nanotube Flexible Strain Sensors with High Sensitivity (Chang and others 2003)

Single-walled nanotubes have excellent mechanical, electrical, and electromechanical properties that make them suitable for strain and pressure sensors, especially when used with silicon substrate. Chang and others focus on the fabrication of "high sensitivity SWCNT flexible sensors. The individual millimeter-long suspended SWCNTs are transferred at room temperature from silicon wafer to flexible substrate that already has preetched trench and electrodes." This type of sensor has better adhesion and can be "effectively strained along its length and also avoid the interference with the flexible substrates during strain sensing measurements."

"The completed sensor composed of a SWCNT crossing the prefabricated trench between two electrodes on the flexible substrate … was glued on a plastic cantilever beam for strain sensing measurements." To provide an electrical voltage to drive the linear VCM, a function generator was used. The results from the mechanical bending test resulted in a strain sensor with a sensitivity of 0.004%. The piezoresistive gauge factor was 269, higher than the typical metal strain gauges (1–5) and the state-of-the-art doped–Si strain sensors (200).

Nanoelectromechanical Sensors Based on Carbon Nanotubes (Hierold and others 2007)

The area of nanoelectromechanical systems (NEMS) has had a lot of attention because of its potential to fabricate high-sensitive low-power sensing devices. Hierold and others (2007) focused on creating NEMS out of carbon nanotubes (CNTs).

The electromechanical properties of single-wall carbon nanotubes (SWNTs) make them have a great variety of application as piezoresistors. Other properties that they possess include the following:

- Ability to exhibit metallic or semiconducting behavior depending on the "structural symmetry, which is described by the terms armchair, zig-zag or chiral type tubes."
- Young's modulus of 1 TPa.
- Hollow cylinders made out of a single layer of carbon atoms.
- Lengths are in the micro-scale, while the diameters are in the order of 1 nm.

Many different methods are available to produce carbon nanotubes. Arc-discharge, laser ablation, and chemical vapor deposition (CVD) are all viable methods. "Arc-discharge and lase ablation … involve the condensation of carbon atoms generated from evaporation of solid carbon sources." They produce entangled nanotubes or nanowires, a process known as "bulk" growth. This creates a challenge for "post-growth purification, manipulation and assembly." "CVD allows for controlled surface-bound SWNT growth enabling device integration." This process involves using a catalyst material and heating it to aid in the growth of the SWNT.

Sensors and devices "for direct and reliable measurements of nanotube transducer properties" can be created by integrating nanotube growth into a fabricated microsystem. This device was then integrated to MEMS-like structures.

A concept for a nanoscale force sensor was developed. The functionality of the device is thus described: "an individual

SWNT is connected to and fixed by electrodes and it is suspended from the substrate. If an external out-of-plane force acts on the freestanding cantilever, it will deflect, which finally leads to a mechanical deformation of the clamped SWNT." To test the concept, a cantilever and bridge-based structure were studied by actuating with an atomic force microscope. The results were that the "concept of nanoelectromechanical system" could be proven.

A member-based CNT transducer was also demonstrated. The benefit of the membrane-based test is that the deformation of the nanotube at "the edges of the cantilevers or bridges is avoided and axial stress is applied to the tube by straining the membrane." This device works as a SWNT-based pressure sensor. Ultimately, this research confirmed the use of SWNTs for sensors "by the integration of tubes in well-defined MEMS structures."

Nanoelectromechanical Devices for Sensing Applications (Cimalla and others 2007)

Nanoelectromechanical systems (NEMS) have had the interest of the technical and scientific communities, mainly because of the devices' "high resonant frequencies, miniscule active masses and a mechanical quality factor Q in the range of 10^3 to 10^5." The basic configurations for resonant devices are the singly and doubly clamped beams. The device being fabricated has to work for chemical and biological sensing applications. The device has to work under ambient conditions, which can include liquid media. "In this paper, we will focus on a reasonable compromise which allows the detection of small mass loadings while remaining under ambient conditions … we study the different internal and external damping influences in order to increase the quality factor in vacuo to its upper limit."

Two resonators were developed: one with AlN (Aluminum Nitrogren) and the other one with SiC (Silicon Carbon). The fabrication process started with the use of a Si wafer. SiC layers 0.2 µm thick were grown heteroepitaxially, using high-vacuum chemical vapor deposition (HVCVD) at around 900 °C and a pressure of 1×10^{-9} mbar. (For the AIN, different thicknesses were "deposited by reactive sputtering on Si substrates at varying substrate temperatures—100–500 °C. Optical and UV-lithography were used to establish the beam dimensions (width of 0.5–8 µm and a length of 5–500 µm). Further reduction to a width of 100 nm was done by using e-beam lithography.

The resonators work using magnetomotive actuation. The "Lorentz force drives a conductor when exposed to an external magnetic field." The beams were placed in a magnetic field of 0.5 T and "an adjustable RF [radio frequency] current caused them to oscillate." A pulsed-measurement technique was used for the experimental characterization of the beams, in which "excitation and response signal can be separated in the time domain."

When the resonator was put under mass loading, the response followed a linear dependence. "The resonant frequency and the quality factor of a cantilever oscillating in a gaseous environment depend on the pressure of the gas. When the pressure is increased, both parameters will decrease." The thermal expansion of the resonator beam will directly affect the internal strain of the beam. "The sensitivity drops by more than one order of magnitude if the full structure is isothermally heated."

Nanoengineering Beyond Nanoelectronics (Rohrer 1998)

One "economically rewarding aspect of nanotechnology is the continuation of miniaturization from today's microelectronics to tomorrow's nanoelectronics." A way of summarizing the importance of the nanotechnology is to make the materials "smaller, faster, [and] cheaper." Miniaturization is extended to time, price, and energy costs.

Polyisoprene–Multi-wall Carbon Nanotube Composites for Sensing Strain (Knite and others 2007)

There is a definite need for developing large and flexible sensors that can be embedded and placed in different places of the material. Polymer-electro-conductive nanostructure composite (PENC) is an attractive alternative in developing large and flexible sensors. Knite and others talk about the design, elaboration, and investigation "of the polyisoprene and multiwall carbon nanotube (MWCNT) composites for application in strain sensors as well as to compare them with the polyisoprene and high structure carbon black (HSCB) composites elaborated and prepared by the same technology."

Polyisoprene composites that contained dispersed nano-size particles, either MWCNT or HSCB, were used using the "solution method" to create the film. The procedure can be found in the literature. Once the materials were created, samples were taken both from the HSCB and MWCNT vulcanized sheets. These samples were used to study the deformation and dependence of electrical resistance. "Copper foil electrodes were glued on both sides at the ends and each pair of electrodes was short-circuited by copper wiring … sandpaper was glued to the electrodes to fasten the samples in the stretching machine (extensometer)."

The reversible change in the electric resistivity at large stretch on the polyisoprene matrix filled with MWCNT was of four orders of magnitude. Multiwalled carbon nanotube-polyisoprene composite is better for small tensile strain sensing, while the one with the high structure carbon black polyisoprene composite works better for large strains.

Strain Sensing Using a Multiwalled Carbon Nanotube Film (Vemuru and others 2009)

"Conventional strain gauges" have a limitation regarding the direction of strain that they can measure, as well as limitations on the locations in which they can be placed. These limitations produce a need for the development of a multidirectional and multifunctional sensor. Nanotubes are excellent materials for this as they have a small size, low density, high stiffness, high strength, and good electronic properties.

Single-walled carbon nanotubes have been studied in sensing applications. Although these nanotubes are a great material for sensing applications, they present some challenges. “The use of single-walled carbon nanotubes is restricted by limited control of the purity, chirality, and electrical properties of single-walled carbon nanotubes produced by the available synthesis process.” Multiwalled carbon nanotubes are more economical and can be produced at a high purity level. Vemuru and others used MWCNT film for sensing applications.

The MWCNT films were from a private organization. To test the nanotube film, it was attached to a 12- × 2.5- × 0.25-in. brass specimen. The brass specimen had an elastic (Young’s) modulus of 166 GPa. An epoxy coating was applied between the film and the brass specimen. A conventional strain gauge was placed on the other side of the specimen to verify the readings of the nanotube film and used for comparison. “A four-point probe [was] attached to the carbon nanotube film by using silver epoxy. The brass specimen [was] subjected to uniaxial tension in a servo hydraulic test frame, and current passed through the outer two probes.” Temperature was also taken into consideration. “The brass bar [was] heated using a heater, and the temperature [was] measured using a thermocouple.” The specimen was clamped in a universal testing machine without any load while the change of voltage as a function of temperature was measured.

Based on limited test results, Vemuru and others concluded that MWCNT film used as a strain sensor at the macroscale was very encouraging. There was a linear relationship between the change of voltage in the MWCNT film and the strain of the brass specimen. The film responded well to loading and unloading. The temperature effects on the specimen based on the tests, although having limited responses, seemed to have an excellent predictable voltage response.

Wireless Impendance Sensor Nodes for Functions of Structural Damage Identification and Sensor Self-Diagnosis (Park and others 2009)

There is a need to monitor infrastructure, especially after the accidents of the Seong-Su bridge in Korea and the I-35W bridge in Minneapolis. Researchers found that these accidents happened because of local failure on critical members. Existing methods, such as nondestructive evaluation techniques and acceleration-based modal testing monitor structural health. Examples of these can be the electromechanical impedance-based damage detection technique and the micro-electromechanical systems and radio frequency telemetry. There was a need to develop an “improved wireless impedance sensor node with both functions of structural damage identification and sensor self-diagnosis.”

Piezoelectric actuators recognize when an electric field is applied via the generation of a mechanical strain (proportional to the electric field). A piezoelectric sensor develops a voltage proportional to a mechanical pressure applied. “Electromechanical impedance-based SHM techniques utilize small PZT [lead-zirconate-titanate] patches attached to a host structure as self-sensing actuators to excite the structure with high frequency excitations and monitor the changes in the electrical impedance of the patch.”

Research is being conducted to develop a wireless active sensor node that incorporates “on-board actuating/sensing, power generation, on-board data processing/damage diagnostics and RF module is being heavily investigated.” A prototype was developed that incorporates a temperature sensor, a multiplexer, and external memory (SD card slot). Environmental conditions, such as temperature, have an impact on the impedance-based SHM techniques. Therefore, temperature readings have to be measured and corresponding compensation techniques are required. Multiplexing is helpful, as it is important to minimize the number of sensor nodes. By doing this, there are savings in resources and efforts.

Multiple tests were performed to measure the structural damage identification and sensor self-diagnosis. “Two kinds of structural damage identification experiments were performed in detecting cut damage on an aluminum plate and in inspecting loosened bolts on a bolt-jointed steel plate.” At the end of the experiments, Park and others concluded that the sensor works for measuring this type of damage detection. Also, “piezoelectric sensor self-diagnosis experiments were carried out in monitoring the PZT sensor’s defects (fracture condition) and in detecting the bonding layer’s defects (debonding condition).” At the end of the tests it was seen that the “PZT sensor self-diagnosis would not be practical under temperature varying environment.” Because of this, an algorithm that compensates for the variation of temperature was developed.

Structural Health Monitoring

Conformable Single-Walled Carbon Nanotube Thin Film Strain Sensors for Structural Monitoring (Loh and others 2005)

Foil-based strain gauges perform successfully in measuring strain deformations. For long-term field installation, they are not practical because of their low sensitivity and drift properties. A strain gauge with high strain factors can be developed by creating a thin film of single-walled carbon nanotubes and polyelectrolytes (SWNT and PE) in a layer-by-layer approach. The properties of the SWNT make it an excellent engineering material. It has good “mechanical strength, electrical conductivity, and mass density.” After much research, Loh and others was found that “… the general consensus is that SWNT out-performs steel in terms of elasticity and ultimate strength.” The SWNT composite was expected to have "linear changes in conductivity (resistivity)."

The fabrication of the composite film is as follows. Bare glass substrate was dropped into a polyelectrolyte bath. The electrolyte chosen was the polyvinyl alcohol (PVA). The substrate and the PVA were set and then the substrate was removed. It was then rinsed using deionized water. This substrate was later placed in a solution of dispersed SWNT. It was then rinsed again, using deionized water. This process is done until all the layers needed were present. Films were then removed from the glass substrate by using a razor blade. Hydrofluoric solution may also be used.

To test this sensor, two testing methods were employed: the monotonic tensile test and the four-point bending test. After performing the monotonic tensile test, Loh and others concluded that the material had good sensing capabilities. The result of the four-point bending test suggests that "the behavior of the SWNT-PE thin film correlates well with the change in resistance of the reference gauge. However, it is observed that there appears to be a mild drift in the film resistance over time."

Piezoceramic and Nanotube Materials for Health Monitoring (Schulz and others 2003)

Structural health monitoring (SHM) is not frequently implemented. The reasoning for this scarcity may be the inconvenience of the multitude of sensors required to take the measurements. "Interconnected sensors and parallel processing may simplify and make SHM more practical." To do this, nodes can be created by using piezoceramic fibers and perhaps nanotube fibers. The active fiber sensors have unidirectional sensing and are self-powered. They are also efficient for sensing acoustic waves because of their high bandwidth and high voltage. An artificial neuron system can be developed by using smart materials, microelectronics and a new signal processing. "The receptor and dendrite are modeled together using active fibers."

Carbon nanotubes (as well as the single-wall boron nitride nanotubes (BNT), "which are structurally equivalent to carbon," are good materials for the reinforcing and actuating of polymer composite materials. Some of the characteristics and properties of CNTs are the following:

- Length/diameter ratio of 10,000
- Elastic Young's modulus of 1 TPa
- Tensile strength of 50 GPa
- Density of 1.4 g/cm^3
- Actuation energy density 30–100 times greater than existing smart materials
- High temperature capabilities
- "When loaded in compression, the tubes will bend over to large angles then ripple and buckle. However, these deformations are elastic. Upon removal of the load, the nanotube will return to its original undeformed shaped. With the property of superelasticity, if nanotubes could be put together to make macro-scale structures, these structures might become almost unbreakable."

"Raman spectroscopy can be used to characterize single-wall and multi-wall nanotubes. The intensities of the low frequency radial and high frequency tangential modes of single-wall carbon nanotubes exhibit strong resonance effects related to the tube diameter, and the frequency of the radial mode is inversely proportional to the radius of the tube." This can be used to determine the radius of the single-wall nanotube. Raman spectroscopy can also show the stress distribution using "single-wall nanotubes seeded in a composite material." A limitation involved with Raman spectroscopy involves its difficulty of implementation. The conductance in carbon nanotubes can easily be changed depending on external factors. This characteristic makes it a possible sensing material for artificial nerves and monitoring conductance. The carbon nanotubes can be affected by temperature, thus the nanotubes can also be used as temperature sensors. However, the resistance of carbon nanotubes remains constant. This property can further explain the use of carbon nanotube ropes for a long neural system.

There are also non-carbon tubes that could be used as sensors/actuators, boron nitride nanotubes. They have promising characteristics that "offer the possibility of piezoelectric actuation tailored over a wide bandwidth," including good thermal, electrical, and mechanical properties, as well as the opportunity of dipolar bonding. A setback for this material is that it has not been thoroughly experimented with enough to draw legitimate conclusions regarding its effectiveness.

Single-Wall Carbon Nanotube-Based Structural Health Sensing Materials (Watkins and others 2004)

Single-wall carbon nanotubes have excellent qualities. They are one of the strongest materials around (1 TPa, 10 times greater than steel) and can also display semiconducting or metallic behavior, depending on the chirality. These characteristics, as well as many others, make it great for sensing applications, as well as for composite material development.

"The sensors were constructed using conventional lithographic techniques to pattern electrodes on both silicon and flexible plastic substrate. SWCNTs were then deposited and aligned using a dielectrophoretic technique and the resulting SWCNTs created electrical bridges between electrodes." However, tests on these sensors were still under way when the report from Watkins and others (2004) was being prepared.

Structural Health Monitoring of Glass Fiber Reinforced Composites Using Embedded Carbon Nanotube (CNT) Fibers (Alexopoulos and others 2010)

There has been a need to create a fiber reinforced polymer with self-sensing characteristics. By doing this, the safety of the structure is increased and it reduces the "intervals of maintenance" needed on the material. To accomplish this, special attention must be given to the sensors. The materials should be small, lightweight, able to work continuously, and have high sensitivity. If used in the glass fiber-reinforced composite, CNTs increase the electrical conductivity of the "epoxy matrix." This effect can be used to monitor the structural health by establishing "correlations between internal damage and increase in resistance." If carbon nanotubes are displaced in the matrix of the glass, reinforced polymer can be used for self-diagnosing uses.

For a well-functioning composite material, the fibers used for the monitoring of the damage have to have "the same or lower modulus of elasticity and higher ductility." This is why the CNT fibers work perfectly for sensing GFRPs [glass fiber reinforced polymers]. For Alexopoulos and others (2010), CNT fibers were embedded to "seek simultaneously the material's response to mechanical load and its sensing capability by means of electrical resistance change in the CNT fiber."

To test the fiber-reinforced glass composites, two tests were conducted: the tensile and three-point bending tests. From the tensile test, it can be said that the CNT fiber works for sensing tension. The three-point bending tests concluded that the CNT fiber works for tension and compression loadings.

Structural Health Monitoring Using Continuous Sensors and Neural Network Analysis (Lee and others 2006)

Different algorithms have been presented to evaluate structural health monitoring (SHM). In large structures, these algorithms may contain "many practical problems to be resolved, especially for detecting small or hidden cracks." "Impacts and damage such as cracks and delamination that are breathing and propagating can be identified by the waves they generate in the structure." Neural network (NN) analysis is used "to estimate and predict damage in complex structures." The techniques for NN analysis are based on the back propagation neural network.

Lamb Wave Propagation—Wave Simulation Algorithm (WSA) "that uses a modal superposition solution was used for this study." The response given by WSA presents the "time history" of the response. The model of the plate used to measure the antisymmetric bending wave is based on classical thin plate theory. This algorithm is good for measuring wave propagation because "wave reflections from the boundaries are contained in the solution." "Symmetric Lamb waves occur at higher frequencies than the bending waves, have smaller amplitude, are more difficult to sense and are not modeled in this simulation." The simulation previously mentioned is efficient for the study of sensor design and wave reflections. By using this, finite element methods do not need to be implemented. An important note is that wave propagation is important but not the exact wave speed. The arrival of the waves and the peak amplitudes are the important information needed from the continuous sensor (Lee and others 2006).

Neural Network (NN) Analysis Technique—"A popular neural network model is the multi-layer perception neural network." For this study, there was an input layer that measures the strain responses, two hidden layers, and an output layer that locates the damage. The standard back-propagation algorithm is the method used. It has a forward and a backward process. This corrects the strain readings and minimizes the error.

Fabrication of the Long Continuous Sensor—"The long continuous sensor can be formed by connecting in series plurality of discrete monolithic PZT (piezoelectric transducer) sensors spaced appropriately to detect the waves of interest." "A limitation of the carbon nanotube neuron" is that it has a small bandwidth.

The artificial neural system can be formed by using a long continuous sensor. "The neurons can be interconnected to form a neural system, designed as a grid, and attached to the surface of a structure as a sensor layer that acts like the neural system in the human body."

"It was found that most of the assumed damages could be detected successfully. It was also found that the damages could be successfully identified with the noisy response data if the NIL (noise injection learning) was implemented." The long continuous sensor has to be fabricated to verify the "response characteristics of the ANS for practical application of the method in the near future."

Health Monitoring of Civil Infrastructure (Chang and others 2003)

There is a need for maintaining the civil infrastructure's safety and reliability. Health monitoring aids in determining and tracking the structural integrity of the infrastructure. "State-of-the-art methods of health monitoring do not give sufficiently accurate information to determine the extent of the damage." The current methods are "global health monitoring" and "local health monitoring." Global health monitoring identifies the presence of any damage present in the entire structure. Local health monitoring identifies the exact location and extent of the damage. This can be achieved by using non-destructive evaluation (NDE), but these processes can be expensive and time consuming. For this reason, for the SHM of bridges, the most common method is global health monitoring. Other tests performed on bridges include visual inspection and tap tests.

"Most global health monitoring methods are centered on either finding shifts in resonant frequencies or changes in structural mode shapes." Structural health monitoring in its earliest stages found that if a single member in the structure is lost, it affects the fundamental natural frequency. This member loss can also change the stability of the structure.

Another method that can be used is to use the natural frequency shift to determine the length and location of cracks. "The only form of damage is cracking, and by extension loss of cross sectional areas." The matrix update method is another type of global health monitoring. This method is "based on the modification of the mass, stiffness and damping matrices of the structure to match measured data as closely as possible." An issue associated with this method is the reliability of these matrices. Other methods use statistical analysis to determine the probable damage on a structure by "comparing the relative damage probabilities of different damage events." The data used are taken from "continuous or periodic ambient or forced vibration measurements." Last, one of the methods that has recently been developed is the Artificial Neural Network (ANN). This method can recognize strain measurements by comparing them to a "set of training examples that represent different types of damage." The readings are usually better if the damage on the structure is severe. The reliability of this method can be questioned because of the effect that temperature and moisture variations have on the readings.

In the United States, recent developments have found new methods for SHM. One of these methods involves using imaging and pattern recognition. The goal for these methods is to retain the cracks on the image. There is also another approach: the Damage Locating Vector (DLV). This method measures the "changes in flexibility to the spatial distribution of damage." A different approach involves the use of wavelet. It involves the analysis of local data with a "zoom effect." In a time-frequency plot, the damage and the moment of the damage can be detected. This method is recommended for continuous monitoring. Finally, another method uses sensors and actuators, usually made out of a piezoelectric material. This method often involves placing a patch that acts as a sensor and actuator in a vulnerable area.

Different types of sensors have been developed for SHM. The micro-electromechanical system devices have been developed and are used for accelerometers. Magnetic resonance capsules are used to find chloride ions and to "detect out-of-plane displacements caused by delamination." LIDAR (Light Detection and Ranging) is used to identify the three dimensional position of objects. Acoustic technology has been developed that is able to identify the condition of the infrastructure. X-rays and gamma ray technology have been used to study and verify the conditions of the structural elements. Fiber optic sensors are able to measure and count the cracks in concrete. It is a very useful sensor but it has its limitations. The biggest issue that it has is that it is complicated to place on the bridge, requires skilled labor, and the data collector equipment is expensive. For this reason, new technology is being developed in the field of smart sensors. These would make the data collecting process easier, as the devices process the data before the output is recorded. Sensors are also being developed with the capability of communicating with each other. This concept is called nanodust, which consists of small sensors that communicate to make a powerful network.

Concluding Remarks

The review of currently available literature revealed a large amount of literature related to this topic, nearly all of which is contained in journals with a "high" impact factor. In nearly every case, the literature provides a description of an incremental development of or change in a nanotechnology concept. In the other cases, the authors provide unfounded opinions on potential applications for the yet to be fully developed technologies. Based upon the review of available literature the following concluding remarks are made:

- Developers and researchers of nanotechnology concepts should work hand-in-hand with more application-based researchers to ensure that the developments might lead to useful products.
- With specific respect to timber—it does not appear as though any nanotechnologies are ready for implementation into timber structures. However, there does appear to be several concepts that if successfully developed (especially with an application in mind) might lead to useful nanotechnology concepts.
    - It appears that the primary barrier related to a successful trial implementation is that researchers outside the realm of technology are not developing their technologies with a specific application in mind. Without such an application-specific mindset, it will be difficult for timber researchers to determine which specific technologies might potentially be the most viable.
- The desirable attributes for a nanotechnology that could be integrated into timber structures include the following:
    - Ability to be integrated into fabricated timber elements using current facilities.
    - Ability to detect behaviors and/or deterioration of significance to timber (e.g., decay, moisture ingress, UV degradation).
- Recommended research would work toward modifying existing, early-stage nanotechnologies to have the above mentioned desirable attributes.

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