Carbon Fibres as a Self-Sensing Material For Health Monitoring of Concrete Structures: A Review

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Abstract: Requirements for smart materials and sensors for non destructive health surveillance are growing as critical structures such as bridges, nuclear vessels, chemical storage etc. need to be monitored in real time. During static and dynamic loading, sensors are needed to detect cracks in actual time for damage evaluation with consequent remedy action plan. They are also required to be low cost for large structures to be instrumented. Existing sensors such as strain gauges, fiber optic gauges, piezo electric, acoustic emission, Bragg grating, etc. are not only expensive, but also suffer from bad durability and the need for qualified staff, transportation and erection issues. They also require expensive peripheral equipment such as electronic and laser equipment, while as carbon fiber itself is a sensor and requires no additional equipment except for a few simple instruments.

This study reviews carbon materials for important emerging applications related to structural self-sensing (a structural material that senses its own condition). Self-sensing composites are becoming extremely appealing for civil engineering applications to enhance structural safety and efficiency. These smart composites demonstrate a detectable shift in their electrical resistivity with applied stress or strain and this distinctive feature makes them beneficial for structural health monitoring. To date, various types of carbon composites, i.e. short fibres, continuous fibres, nano fibres, nanotubes, etc., have been used for this purpose.

Keywords: Smart Materials, Sensors, Self-Sensing, Health Monitoring, Static and Dynamic Loading

I. INTRODUCTION

Regardless of long service life of civil engineering structures, they cannot be considered as maintenance-free. These engineering infrastructures are the most steep investments and assets of any nation. Worldwide incidents of catastrophic failures of civil constructions remind us that appropriate steps are needed to prevent the sudden collapse of civil infrastructure and the related loss of resources and lives. Concrete is most commonly used material in civil engineering structures. Due to some intrinsic drawbacks of concrete, these structures weaken with time. The weakening and failure of concrete structures occurs primarily owing to aggressive environmental circumstances, extended use, material ageing, overloading, absence of maintenance and problems engaged in adequate inspection techniques. Within the microstructure of concrete; it contains numerous cracks in nano-scale. These cracks are formed during manufacturing or use. With time, nano-cracks unite to form micro-cracks, which in turn leads to the creation of macro-cracks and structural failure. Through early detection of these inherent damage, sudden collapse and accidents can be prevented. Timely detection of damage and adequate maintenance can significantly enhance the service life of concrete structures. The process of monitoring of deformation and damage that occur within civil engineering infrastructures is normally known as Structural Health Monitoring (SHM). SHM is highly essential for important civil structures such as nuclear power plants, dams, bridges, high-rise buildings, and power utilities. An active monitoring system can recognize various defects in real time and online and monitor damage, strain and temperatures so that the structures can be optimally maintained to provide sufficient safety and lifespan. Different sensors used in self-sensing concrete are shown in figure 1.

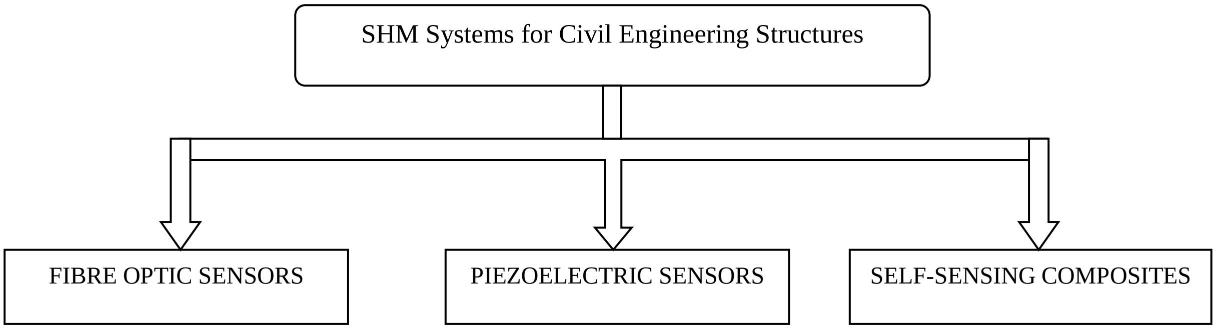

Figure 1: SHM Systems for Civil Engineering Structures

Carbon fibres (alternatively CF, graphite fibre or graphite fibre) are fibres about 5–10 micrometres in diameter and composed mostly of carbon atoms. Carbon fibres have several advantages including high tensile strength, low weight (8 times stronger and 1.5 times lighter than aluminium, 10 times stronger and 5 times lighter than steel), high stiffness, high temperature tolerance, high chemical resistance and low thermal expansion, corrosion-resistance and excellent strength to weight ratio compared to other materials. These properties have made carbon fibre very popular in civil engineering, military, aerospace and motorsports, along with other competition sports.

Self-diagnosing or self-sensing is the property by which a material can nous its own conditions such as strain, temperature, damage, stress, so on and self-sensing composite works are based on piezoresistivity principle. To attain piezoresistivity in a composite material, it should contain a conducting constituent. Different types of conducting components which have been used in self-sensing composite materials are shown in figure 2 below.

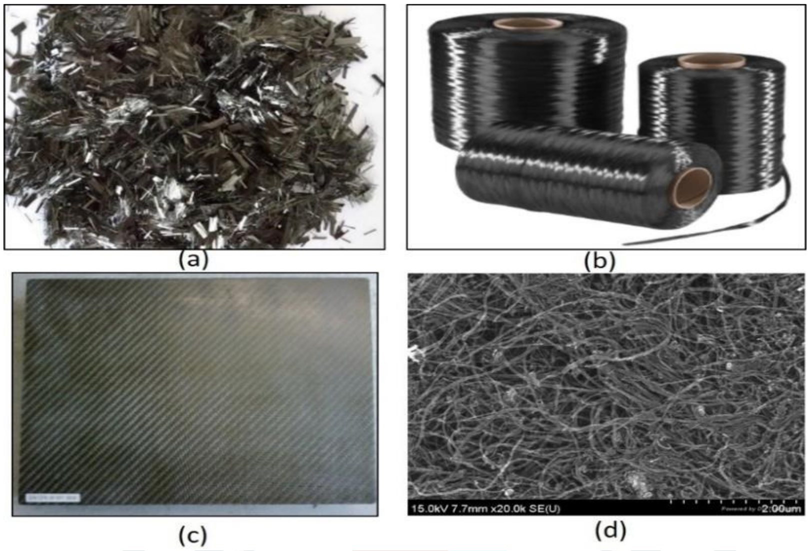

Figure 2: Different electrically conducting elements used for fabricating self-sensing composites: (a) short carbon fibre, (b) carbon yarn, (c) carbon fabric and (d) carbon nanotube.

II. RESEARCH AND STUDIES ON USE OF CARBON FIBERS

Relevant research work and studies are reviewed here:

Schulte K and Baron C (1989) [1] Showed the variation of the mechanical stiffness during fatigue loading. The measurement of the variation of the electrical resistivity during loading promised to be a valuable technique for this purpose. In the case of a conventional metal sample, the conductivity is essentially the same for any direction of current flow through the sample. In carbon fibre reinforced plastics samples, the conductivity is not isotropic and depends on the orientation and on the conductivity of the carbon fibres. Changes in the conductivity could therefore be related to fibre fracture. The resistivity also varies with temperature, and it was therefore necessary to correlate resistivity changes with the temperature changes observed during a fatigue test. The resistivity of carbon fibre reinforced plastics laminates is further dependent on the applied load, the fibre volume fraction, the laminate stacking sequence and the fibre type. Measurement of the electrical resistivity could be used in situ to detect damage in a carbon/epoxy specimen or component under load, electrical resistivity varies directly as a result of the actual strain or load and the measurement of resistivity in a carbon fibre reinforced plastics component is a non-destructive evaluation (NDE) technique, with which composite parts can be inspected even when they are in use. The inspection could be continuous or intermittent.

Ogi K and Takao Y (2005) [2] Aimed at characterizing the piezoresistance behaviour in a carbon fibre reinforced plastics (CFRP) unidirectional laminate under mechanical loading. A 2-dimensional model is proposed using a DC (direct current) circuit equivalent to an electric resistance network in the laminate to predict the resistance change due to tensile loading. The surface resistivity and the initial gage factor are expressed as a function of the off-axis angle in the model. The piezoresistance performance in the fibre and transverse directions is predicted based on the resistance model coupled with the probabilistic failure of conduction paths parallel and perpendicular to the fibre direction. The measured resistance in these directions increases linearly within the small tensile strain, while it increases non-linearly at large strains. The measured resistance in the off-axis directions exhibits remarkable non-linearity except the first linear region. The predicted initial gage factor becomes the maximum at an off-axis angle of 12^0 and is in reasonably good agreement with the experimental results.

Chen B (2008) [3] Monitored damage in carbon fibre-reinforced concrete (CFRC) under uniaxial compression and three-point-bending conditions by both acoustic emission (AE) analysis and electrical resistance measurement. For CFRC, the electrical conductivity depends on the percolation network formed by the contacting carbon fibre. Classical AE technique was applied to verify the reliability of resistance measurement. The results showed that electrical resistance measurement is capable to monitor in-situ evolution of various internal damage in carbon fibre-reinforced concrete. Under uniaxial compression, the initial resistance of specimens decreased with the increase of the load. When the load reached 60% of failure load (i.e. significant damage occurred in the specimens), the resistance increased significantly. There was good correlation between the relative change of resistance and load–deflection curves under three-point bending. The comparison of analysis between electrical resistance measurement and AE technique indicated that these two techniques are complementary for monitoring damage in CFRC.

Wang W, Dai H et al. (2008) [4] Introduced a new CFRC-strengthened RC beam model which can both strengthen and monitor the large-scale RC element used in concrete infrastructures. An experiment of testing four-point bending beams was proceeded in order to analyze mechanical behaviour and electrical property of the designed beam under monotonic loading as well as the relationship between fatigue damage and electrical property under cyclic flexural loading. The analytical results pointed out that this innovative CFRC- strengthened beam has better flexural performance due to the superior cracking resistance capacity of the CFRC layer. Moreover, the change in electrical resistance of the beam was detected under monotonic loading. The first cracking load, the ultimate load and the stiffness of the CFRC-strengthened beam are slightly larger than that of the virgin RC (reinforced concrete) beam due to the improved cracking resistance capacity of the CFRC layer. The damage condition in the CFRC-strengthened RC beam can be monitored by electrical resistance measurement. The degree of strengthening influences the electrical property of the beam, the thicker the CFRC layer, the smaller the initial electrical resistance, and the larger the electrical resistance increases under fatigue and monotonic loading.

Gao D et al. (2010) [5] Studied the mechanical and electrical properties of concrete containing carbon nanofibres (CNF). The compressive strength and percent reduction in electrical resistance while loading concrete containing CNF (carbon nanofibre) are much greater than those of plain concrete. A reasonable concentration of CNF (carbon nanofibre) was obtained for use in concrete which not only enhanced compressive strength, but also improved the electrical properties required for strain monitoring, damage evaluation and self-health monitoring of concrete. Well-dispersed CNF (carbon nanofibre) improved the strength and stiffness of concrete mix. Excess concentration led to poorly dispersed CNF (carbon nanofibre) clumps inside the concrete and had a negative effect on both strength and electrical sensitivity. CNF (carbon nanofibre) decreased the electrical resistance of SCC (self-consolidating concrete) because it is a semiconductor, but there is a threshold for fibre concentration. Crossing threshold, the tunnel conductivity effect of CNF (carbon nanofibre) would decrease and the electrical resistance does not change with increasing strain.

Howser R. N, Dhonde H. B et al. (2011) [6] Investigated self-consolidating concrete with steel fibres and carbon nanofibres in shear-critical columns and the performance was compared to a conventional self-consolidating reinforced concrete column. Tests results were studied under reversed static loads of three columns. The three columns consist of a traditionally reinforced concrete (SCRC) column that serves as a control specimen, a self-consolidating steel fibre concrete (SCSFC) column that does not contain transverse reinforcement and a self-consolidating carbon nanofibre concrete (SCCNFC) column. 1% steel fibres by volume effectively replaced all of the transverse reinforcement in a shear critical column. The steel fibres were found to increase both the shear and flexural strength of the column. The addition of CNF (Carbon nanofibre) to concrete increased the strength and ductility of a column. The SCCNFC column had an ultimate normalized capacity that was 30.7% higher and a deflection that was 34.9% higher than the SCRC column. The ductility of the SCCNFC column was 35.1% higher than the SCRC column's ductility.

Rana S, Alagirusamy R et al. (2011) [7] Investigated on the various techniques for dispersing CNFs in an epoxy resin such as ultrasonication, high speed mechanical stirring and the use of solvent, surfactant and higher temperature. Vapour-grown CNFs (Carbon nanofibre) was uniformly dispersed in the matrix of carbon/epoxy composites using ultrasonic treatment assisted with high speed mechanical stirring. This dispersion technique had led to a significant enhancement in Young's modulus and fracture toughness and highest improvement in tensile strength of epoxy among the all dispersed routes. Dispersion of only 0.5% CNF in the matrix improved Young's modulus and tensile strength of carbon/epoxy composites by 37% and 18% respectively. Similarly, compressive modulus and strength improved by 50% and 18% respectively. Improved mechanical properties of three phase composites is attributed to the formation of strong interface between carbon fibres and epoxy matrix in the presence of CNFs. Due to superior electrical and thermal conductivity of vapour-grown CNFs, their incorporation in the matrix of carbon/epoxy composite resulted in improved thermal and electrical conductivity even at very less CNF concentrations (up to 1.0%).

Chung D. D. L (2012) [8] Reviewed the carbon materials for significant rising applications related to structural self-sensing (a structural material sensing its own condition), thermal interfacing (improving thermal contacts by using thermal interface materials) and electromagnetic interference shielding (blocking radio wave). High-performance and cost-effective materials in various forms of carbon had been developed for these applications. The forms of carbon materials include carbon fibre, carbon nanofibre, exfoliated graphite, carbon black and composite materials. Short carbon fibre cement-matrix composites and continuous carbon fibre polymer-matrix composites are particularly effective for structural self-sensing, with the attributes sensed including strain, stress, damage and temperature. Flexible graphite as a monolithic material and nickel-coated carbon nanofibre as a filler are particularly effective for electromagnetic shielding. Carbon black paste, flexible graphite (filled with carbon black paste) and graphite nanoplatelet paste are particularly effective for thermal interfacing; carbon nanotube arrays are less effective than these pastes.

Yu Xun and Kwon Eil (2012) [9] Summarized the development of self-sensing carbon-nanotube (CNT)/cement composites. The piezoresitive property of carbon nanotubes enabled the composite to detect the stress/stain inside the pavement. CNTs (Carbon nanotubes) could also work as the reinforcement elements to improve the strength and toughness of the concrete pavement. Piezoresistive carbon nanotubes cement composites are developed and tested. Experimental results showed that the compressive stress levels of the composite changed proportionally to the electrical resistance. The piezoresistive responses of the composite with different fabrication methods were also studied. The CNT (Carbon nanotubes) acid-treated method showed stronger piezoresistive response and higher signal-to-noise ratio than the surfactant-assistant dispersion method, in which the surfactant could block the contacts among nanotubes, thus impairing the piezoresistive response of the composite. A set of lab and road tests were performed to test the effectiveness of the self-sensing concrete (SCC) by applying dynamic loads under the controlled environment.

Azhari F and Banthia N (2012) [10] Considered two types of cement-based sensors, one with carbon fibres alone and the other carrying a hybrid of both fibres and nanotubes. Electrically conductive cementitious composites carrying carbon fibres (CFS) and carbon nanotubes (CNTS) was developed and their ability to sense an applied compressive load through a measureable change in resistivity was investigated. Direct comparisons were also made with conventional strain gauges mounted on the sensor specimens. Sensing experiments indicated that under cyclic loading, the changes in resistivity mimic both the changes in the applied load and the measured material strain with high fidelity for both sensor types. The response, however, was nonlinear and rate dependent. At an arbitrary loading rate, the hybrid sensor, containing a combination of carbon fibres and nanotubes, produced the best results with better repeatability. Creation of microcracks was signified by a steady increase in the resistivity which then changes to a sudden upsurge when microcracks coalesce and failure occurs. Thus, in addition to strain sensing, these materials can sense microcracking and failure.

Salvado R et al. (2015) [11] Studied the electrical and mechanical behaviour of several continuous carbon fibres epoxy composites for both strengthening and monitoring of structures. In these composites, the arrangement of fibres was purposely diversified to test and comprehend the ability of the composites for self-sensing low strains. Composites with different arrangements of fibres and textile weaves, mainly unidirectional continuous carbon reinforced composites, were tested at the dynamometer. A two-probe method was considered to measure the relative electrical resistance of these composites during loading. The measured comparative electrical resistance includes volume and contact electrical resistances. For all tested specimens, it increased with a raise in tensile strain, at low strain values. Laboratory tests on strengthening of structural elements were also performed, making hand-made composites by the “wet process”, which is commonly used in civil engineering for the strengthening of all types of in-situ structures. Results showed that the woven epoxy composite, used for strengthening of concrete elements is also able to sense low deformations, below 1%. These textile fabrics are low cost, multi-functional material, and lightweight, able to both strengthening and monitoring the health of structures of buildings.

Sathyanarayanan K. S and Sridharan N (2016) [12] Observed self sensing or smart behaviour in mortar or concrete mix with the addition of small quantity (0.2% to 0.5% by volume of cement) of short (5mm length) carbon fibres. It was seen that there is an increase in electrical resistance on loading up to crack propagation or breakage. On reaching the inelastic stage, the resistance change was not reversible. A method was developed which can be used in place of, often used strain gage technique or fibre optic technique for health monitoring of structures. There was an increase in resistance during fibre pull out in the elastic range. The change in elastic resistance was measured by a 4-probe method and was seen to be reversible for elastic deformation. Also, the crack propagation and fibre breakage of the specimen could be identified by irreversible resistance change. The stress vs strain and resistance vs strain graphs when plotted showed similarity. This phenomenon could be made use of to find the real time weight of vehicles in traffic and finding stress values of a loaded structure etc.

Goldfeld Y, Rabinovitch O et al. (2016) [13] Investigated the feasibility of intelligent textile-reinforced concrete structural elements with sensing capabilities. Experimental investigation demonstrated the feasibility of the concept in two applications: monitoring the interaction of the structural element with a wet environment and detecting strains in a mechanically loaded textile-reinforced concrete beam. By detected the changes to the integrative electrical resistance of the carbon tow, the ability of the textile to sense strain and exposure to water is demonstrated. For strain sensing, the hybrid reinforcing textile provides electro-mechanical sensing with a gauge factor 1 and a detectable correlation with the load, strain, and displacement responses. The structural behaviour of the concrete element, reinforced with the sensory textile, revealed a satisfactory structural response in terms of the initial pre-cracked linear behaviour, the post-cracking behaviour, the distribution and width of cracks, the behaviour at ultimate stages, and the mode of failure. At the same time, the structural textile provided continuous electrical readings that, by means of a linear calibration, quantitatively describe and monitor the mechanical state of the structural element.

Nanni F, Ruscito G et al. (2017) [14] Presented self-sensing carbon–glass hybrid structural composites, behaving as ‘guard’ sensors (i.e. they give a warning when fixed loads are reached) was designed, manufactured and tested. Samples contained different carbon/glass fibre ratios was prepared and tested, by performed both mechanical (monotonic and cycle tensile tests) and electrical measurements. The results showed the efficiency of the proposed system and the possibility to design such materials to suit any specific application need. The experimentation demonstrated the possibility to realize self-monitoring CF–GF hybrid composites for widespread applications, giving an alarm signal at different composite %σ ultimate. This goal could be achieved by varying the glass/carbon relative amount, i.e. the load at which carbon fibre failure appears. In particular, earlier warnings at lower composite %σ ultimate were reached with lower CF/GF ratios (15 glass bundles around the carbon core). The prepared materials show interesting monitoring properties during either static monotonic tensile or pseudo-cyclic tests. The advantages of these materials, compared to other more sophisticated monitoring systems, are low production costs and versatility, the ease of fabrication and use, so such materials are suitable for widespread low-cost applications.

III. CONCLUSIONS

Based on the various research carried out by many researchers, it may be concluded that:

1: Carbon materials in various forms such as short fibre, particles, continuous fibre and nanomaterials have been widely researched for the development of health monitoring devices.
2: Apart from self-sensing, carbon fibre has proved phenomenal in case of enhancement of concrete strength whether it may be compressive strength or tensile strength when compared to control mix.
3: Concrete incorporated carbon materials can also be used for Structural Electromagnetic Shielding and Thermal Interfacing and Pavement Structural Health Monitoring.
4: Carbon materials were either integrated straight into cementitious materials for the development of smart concrete or integrated into polymers for the production of self-sensing composites.
5: Self-sensing polymeric composites can be used to strengthen civil constructions as well as to monitor their health.
6: Smart concretes incorporating carbon nanomaterials also show very good sensing performance. However, although carbon-based self-sensing materials offer tremendous opportunities to create efficient health monitoring systems, there are a few critical problems that need to be resolved in the near future.
7: Hybrid carbon composites with other fibers give the option of attaining greater ductility and producing alarm signal well before composite failure. Therefore, they are useful to shun unexpected collapse of structures.
8: The low strain sensitivity of carbon composites can be very much improved by using carbon nanoparticles, nanofibers or nanotubes.
9: Although self-sensing materials based on carbon materials give better sensing efficiency, they are costly and have processing problems. There is also insufficient data in the current literature on the impact of environmental and usage circumstances on the self-sensing performance of the composites produced.
10: Therefore, further study work is highly important for the practical implementation of carbon-based SHM technologies in order to overcome the practical issues in applying these technologies and to reduce costs and improve the affordability of these products.

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