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Critical Analysis on smart self-sensing composite materials for civil engineering applications

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Abstract: *Self-sensing composites are becoming highly attractive for civil engineering applications to improve the safety and performance of structures. These smart composites show a detectable change in their electrical resistivity with applied stress or strain and this unique characteristic make them useful for health monitoring of structures. Till date, different forms of carbon composites, i.e. short fibre, continuous fibre, particles, nano fibres, nanotubes, etc. have been utilized for this purpose. In this context, the present paper reports an overview of different self-sensing composite systems used for the health monitoring of civil engineering structures.*
Keywords: *smart; self-sensing; composite materials; health monitoring*

I. INTRODUCTION

Regardless of long service life of civil engineering infrastructures, they cannot be considered as maintenance-free. These engineering structures are the most expensive investments and assets of any nation. Worldwide incidents of tragic failures of civil infrastructures remind that suitable measures are required to avoid sudden collapse of civil structures and associated loss of money and lives. Concrete is the most extensively used material in civil engineering structures. Due to some inherent.

drawbacks of concrete, these structures weaken with time. The weakening and failure of concrete structures occur mainly due to ageing of materials, aggressive environmental conditions, prolonged usage, overloading, difficulties involved in proper inspection methods, and lack of maintenance [1,2]. Within the microstructure of concrete, it contains numerous cracks in nano-scale. These cracks are formed during manufacturing or use. With time, nano-cracks join to form micro-cracks, which in turn, leads to formation of macro-cracks and failure of structures [3]. Through early detection of these inherent damages, sudden collapse and accidents can be avoided. Timely detection of damages and proper maintenance can greatly enhance the service life of concrete structures.

The process of monitoring of deformation and damage that occur within civil engineering structures is commonly known as Structural Health Monitoring (SHM) [1,2,4,5,6]. 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, in real time and online, recognize different defects and monitor damage, strain, and temperatures so that the optimal maintenance of the structures can be undertaken to provide enough safety and life span [1,2]. In general, a typical SHM system consists of three major components: a sensor system, a data processing system (containing data procuring, storage and transmission systems), and an evaluation system (comprising information management and diagnostic algorithms). The primary step to set-up an SHM system is to use stable and reliable sensing tools or sensors) [1,2]. Different sensors such as fibre optic sensors, piezoelectrics, magnetostrictive sensors, self-sensing composite materials, etc. possess capabilities of sensing various physical and chemical parameters related to the health of civil structures [7–11].

II. SHM SYSTEMS FOR CIVIL ENGINEERING STRUCTURES

2.1. Fibre Optic Sensors

Fibre optic sensors (FOS) are suitable for health monitoring of civil structure due to several reasons such as (a) due to their small size, they can easily embedded within civil structures without affecting their performance, (b) distributed sensing technology can be used to monitor civil structures at various locations, (c) electromagnetic interference does not have any effect on the sensing behavior, (d) can be used to monitor various parameters such as strain, displacement,vibration, cracks, corrosion, and chloride ion concentration, etc. [1,2,4]. However, optical fibres may be fragile and should be encapsulated within a protective material and also it is quite difficult to repair the damages. Many attempts have been made to incorporate FOS in pavements, bridges and buildings and field trials have been taken [12,13]. Figure 1 shows the use of Fibre Bragg Grating (FBG) sensor for monitoring of pavements [13].

2.2. Piezoelectric Sensors

Piezoelectric sensors also offer a number of advantages and are suitable for SHM of civil engineering structures. The advantageous features include their variety of sizes and possibility to incorporate them in very remote and inaccessible locations [1]. They can also be used to harvest energy from pavements due to the movement of the vehicles and generated pressure.

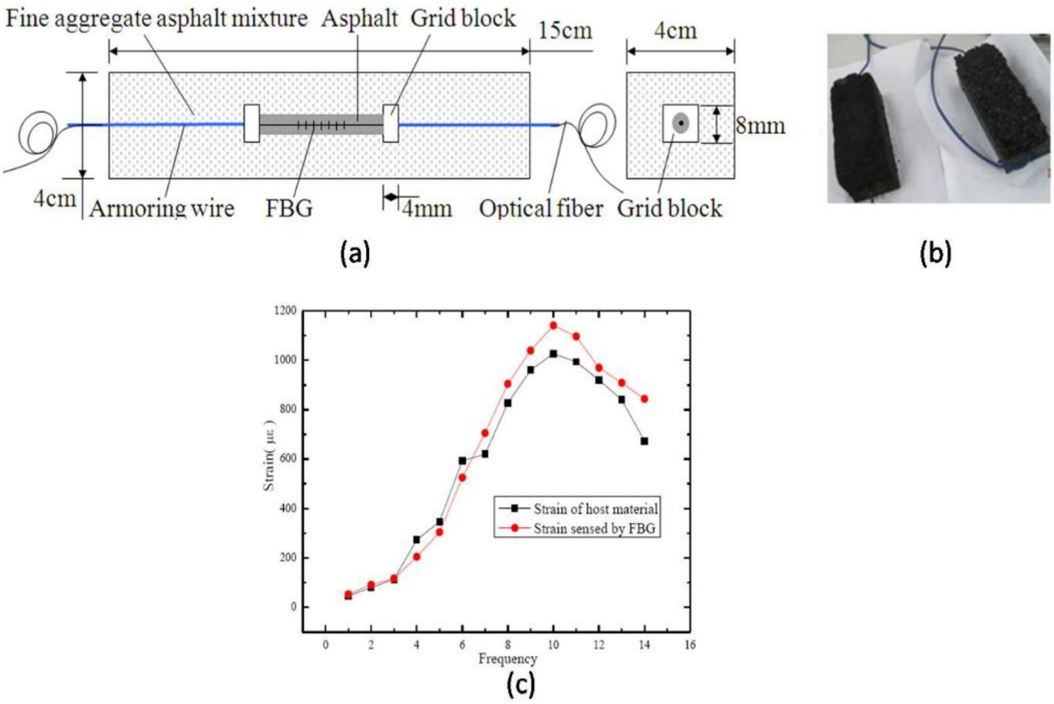

Figure 1. Schematic design of fine aggregate asphalt mixture encapsulated fibre optic sensor (a), real picture (b), and strain sensing capability (c).

2.3. Self-sensing Composites

Self-diagnosing or self-sensing is the property by which a material can sense its own conditions such as stress, strain, damage, temperature, and so on. A self-sensing composite has the ability to sense its own deformation and damage and this ability makes them an excellent material for health monitoring of civil engineering structures. Strain and damage sensing in a composite material is usually achieved through detecting change in their electrical resistivity, i.e. self-sensing composite works based on piezoresistivity principle. One major advantage with the self-sensing composites is the possibility to achieve sensing as well as strengthening of civil structures simultaneously.

To achieve piezo-resistivity in a composite material, it should contain a conducting element. Different types of conducting components have been used in the existing self-sensing composite materials. Short and continuous carbon fibres (CFs), carbon particles as well as carbon nanomaterials such as carbon nanofibers (CNFs) and nanotubes (CNTs) have been utilized for this purpose [14–17], as shown in Figure 2.

These conducting components form a conducting electrical network within the composites. When the composites are subjected to deformation or damage, this conducting network is disturbed leading to a change in the electrical resistivity. The conducting network and resulting change in resistivity are highly dependent on the type of conducting component, their amount as well as their distribution. One of the biggest advantages of self-sensing composites is their design flexibility. The type of response can be tailored easily through proper designing of the composite structure. As mentioned earlier, in civil infrastructures, composites are already in use as strengthening material. Therefore, these composites can also be designed as self-sensing so that they can perform both strengthening and health monitoring functions. This eliminates the need for incorporating sensors from outside for health monitoring of structures. Self-sensing composites can also be based on cementitious materials. Conducting fibres can be introduced directly within the structural elements to obtain the sensing behaviour. Alternatively, sensing composites can be developed by introducing conducting fibres or nanomaterials within polymers or cementitious materials and these sensors can be subsequently introduced within structural elements to perform health monitoring. Different types of self-sensing composites used for the health monitoring of civil structural elements are presented in Figure 3.

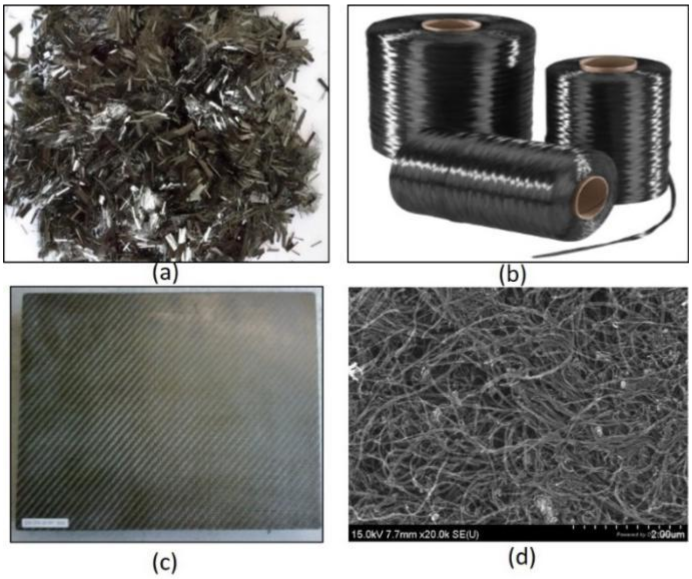

Figure 2. Different electrically conducting elements used for fabricating self-sensing composites: (a) short carbon fibre, (b) carbon yarn, (c) carbon fabric and (d) carbon nanotube.

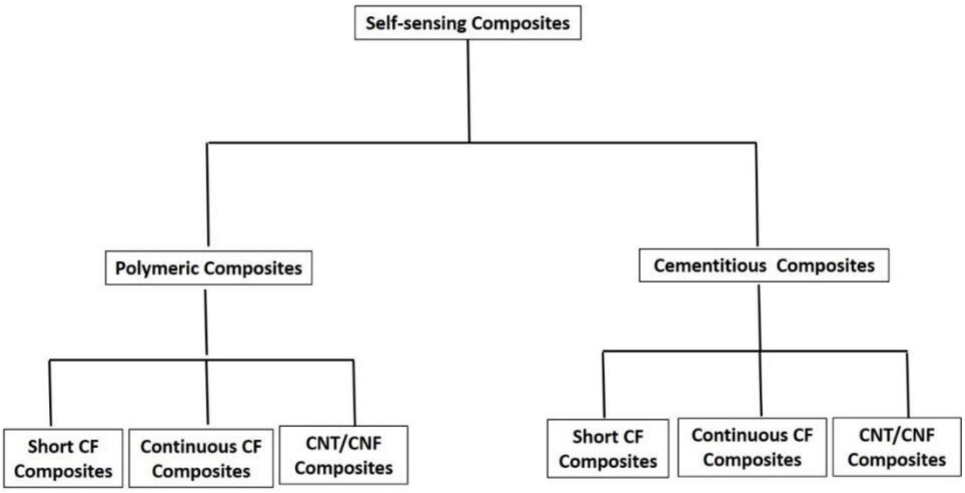

Figure 3. Different types of self-sensing composites for health monitoring of civil structures.

2.4. Characterization of Self-sensing Behaviour

Usually, self-sensing performance of composite materials is quantified by measuring the fractional change in electrical resistance, which is expressed as follows.

Where R0 and R are the initial and final electrical resistances. Also, gauge factor is another frequently used parameter to quantify the self-sensing behaviour of composites. Using the mechanical strain, gauge factor can be calculated as follows.

Electrical resistance in a self-sensing composite can be measured in different ways as shown in Figure 4 [19].

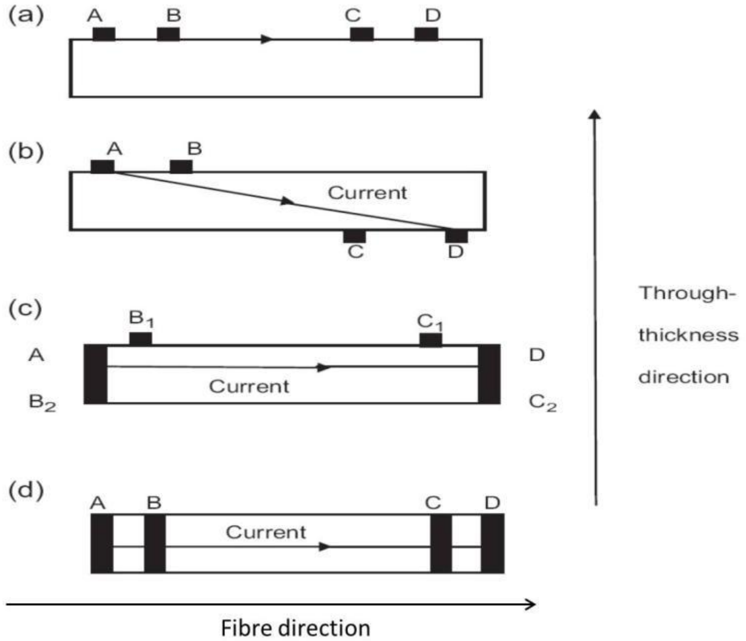

Figure 4. Different methods of electrical resistance measurement in self-sensing laminates.

If the current contacts are on the same surface in the plane of the composite (Figure 4a), the current penetration is in the surface region only. When the current contacts are on the opposite surfaces in the plane of composites, but not located directly opposite to each other, the current penetration can be oblique, as shown in Figure 4b. When the current contacts are on the edge of the composites or located in the holes that goes through the thickness of the composites, the current penetrates through the entire cross-section of the composites, as presented in Figure 4c and 4d. When resistance is measured in the plane of the composites in the direction parallel to the fibres.

III. CARBON SHORT FIBRE BASED SELF-SENSING

Carbon short fibres (CSF) are used as admixtures in cement mixture to improve mechanical performance and incorporate functionalities in to the cementitious materials. When dispersed within cement, short carbon fibres introduce piezo-resistivity and self-sensing property. A self-sensing CSF based cementitious composite has been reported by Wen and Chung [20]. CSFs (0.5 wt.%) with diameter and length of 15 µm and 5 mm were dispersed within Portland cement using a rotary mixer. The self-sensing behaviour of the produced samples was tested under cyclic compressive stress in both longitudinal and transverse directions. The test results demonstrated the damage sensing capability of CSF dispersed cement samples. The damage was sensed by the irreversible increase in resistivity of the specimens under compression. An irreversible increase in both longitudinal and transverse resistivity (Figure 5a and 5b) occurred due to major damages such as breakage of fibres

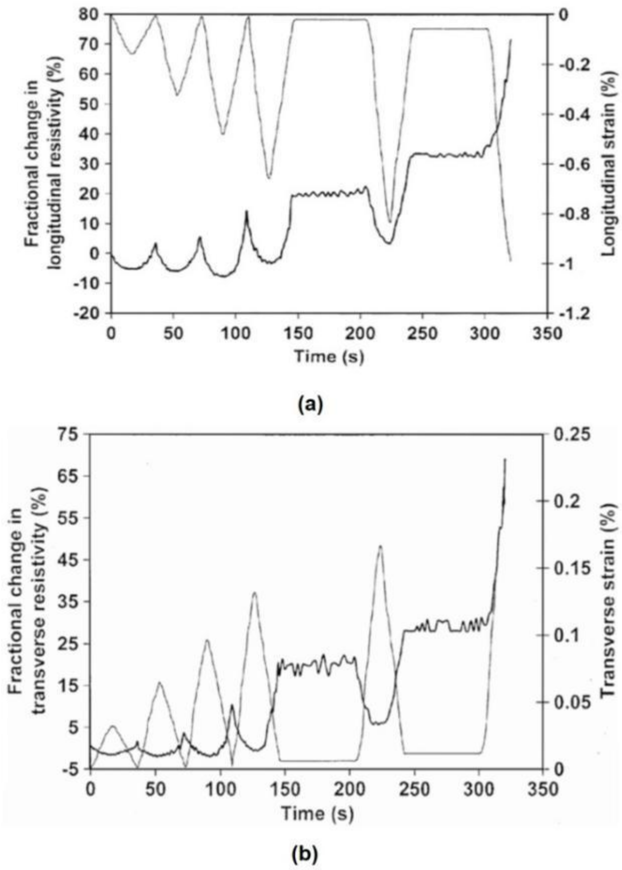

Figure 5. Variation of the fractional change in resistivity (thick curve) with time and strain (thin curve) with time during uniaxial compression at progressively increasing stress amplitudes: (a) longitudinal resistivity and (b) transverse resistivity.

that bridged the micro-cracks. The major damage was sensed by the irreversible increase in the specimen resistivity in the range of 10 to 30%. On the contrary, smaller change in resistivity ranging from 1 to 7% indicated smaller damages in the structure.

Similarly, Wang et al. [21] developed an innovative CSF (5 mm) reinforced concrete beam for sensing of fatigue damage. In this reinforced concrete (RC) beam (shown schematically in Figure 6), CSF reinforced concrete (CFRC) was used as a layer for both self-sensing and strengthening purpose.

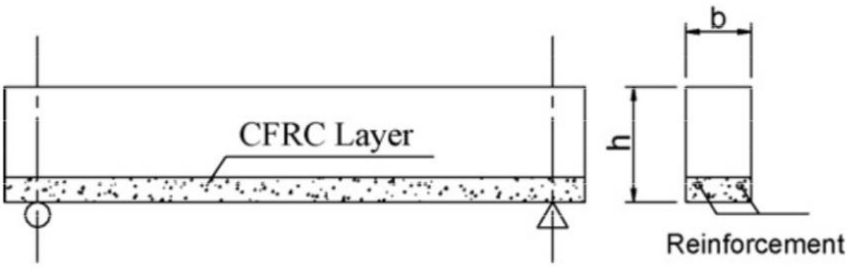

Figure 6. Schematic diagram of CFRC strengthened RC elements.

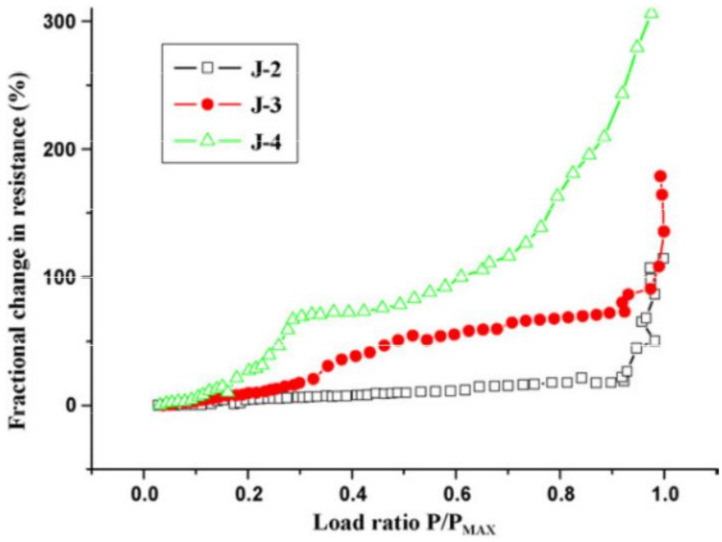

Figure 7. Variation of fractional change in resistance with load of CFRC reinforced beams with different CFRC layer thickness: 30 mm (J-2), 60 mm (J3) and 90 mm (J4).

The trend of fractional resistance change with load under monotonic flexural loading for this type of CFRC is shown in Figure 7. At lower loads, the inherent flaws in the specimens slowly merged to develop new micro-cracks which continued to expand in a stable manner with increasing load. Consequently, due to disturbance in the conducting network, the electrical resistance also continued to increase in a stable manner due to these minor damages. However, when the load increased considerably to the failure load of the specimens, due to the formation of continuous cracks fractional resistance change increased sharply. Under cyclic loading, when the stress amplitude was lower (80% of first cracking stress), only slight damage occurred in the beam resulting in only 7% increase in the fractional resistance change in 50 cycles. On the other hand, when a stress amplitude of 80% of the ultimate stress was applied, the fractional resistance increased irreversibly with the loading cycles, reaching 179% during failure of the beam in 38 cycles, as shown in Figure 8. The irreversibly increased electrical resistance, which is called the "residual resistance", increased with fatigue damage and therefore, can be a useful parameter to monitor fatigue damage in the RC beams. Damage monitoring in concrete structure using CSF has also been reported by Chen and Liu [22].

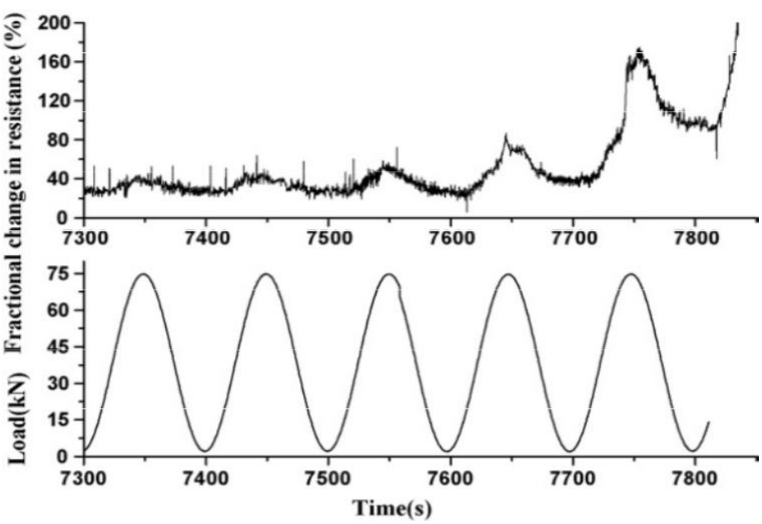

Figure 8. Fractional change in resistance during cyclic flexural loading at last 5 cycles.

Recently, short carbon fibre reinforced polymeric composites have been developed for health monitoring of civil engineering elements [23]. For this purpose, short carbon fibres (1 mm and 3 mm lengths) at various weight % (0.5, 0.75, and 1.25) were dispersed in an unsaturated polyester resin through mechanical stirring. After curing, the short fibre dispersed composites showed excellent strain sensing behaviour, as shown in Figure 9. Chopped fibres with different lengths exhibited similar strain sensitivity which, however, enhanced with the decrease in their concentrations (0.5%). Gauge factor as high as about 36 was obtained with the optimized composites. Therefore, these short fibre dispersed composites can have good potential for strain sensing of civil engineering structures.

IV. Continuous Carbon Fibre Based Self-Sensing

4.1. Carbon Fibre Reinforced Polymeric Composites

Polymeric composites of carbon fibres have been investigated extensively for strengthening as well as self-sensing of structural elements. Different arrangements of carbon fibres such as unidirectional tows and textile fabrics (either woven or knitted) have been used for this purpose. Moreover, hybrid composites of carbon and other fibres (such as glass, aramid, etc.) have also been developed to improve the sensing as well as strengthening capability.

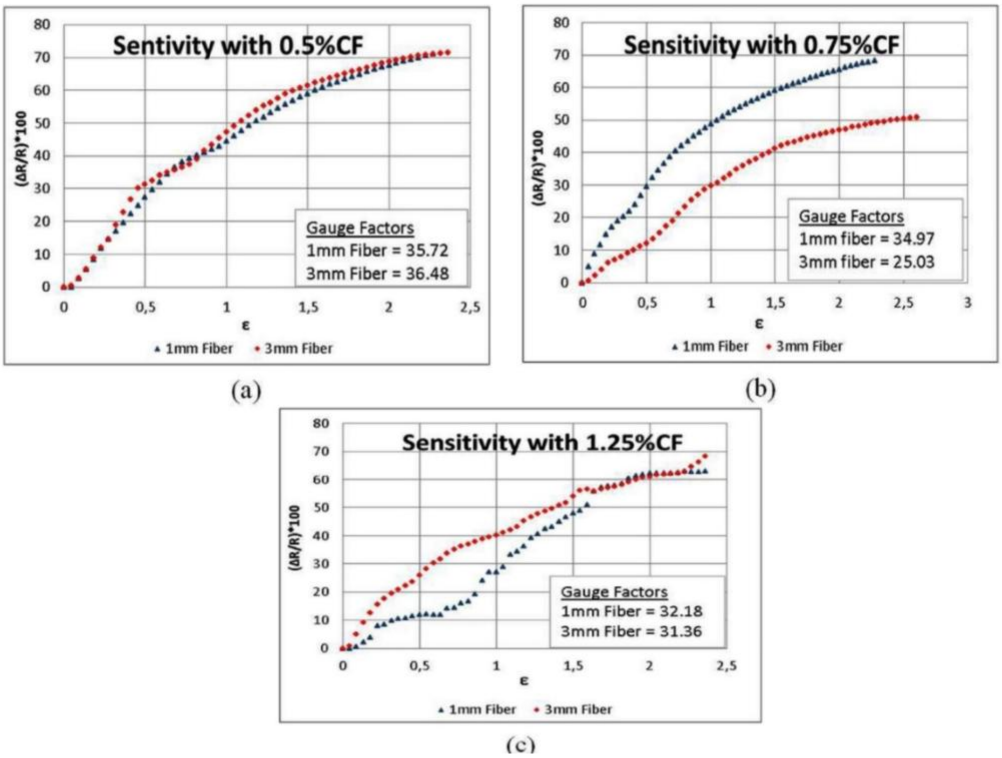

Figure 9. Variation of fractional resistivity of CSF dispersed polyester matrix composites with compressive strain at different concentrations: (a) 0.5%, (b) 0.75% and (c) 1.25%.

Carbon fibre reinforced polymer composites exhibit piezoresistive behaviour under different types of loading [24]. Unidirectional carbon fibre reinforced epoxy composites have been found to sense their own strain in the fibre direction. Upon tensile loading, the longitudinal electrical resistance decreases reversibly with strain and transverse electrical resistance increases [25]. The reason behind the change in electrical resistance with tensile strain is the change in electrical contacts due to change in the fibre alignment. Under tensile loading, the fibres become more aligned in the loading direction leading to increase in the electrical contacts and decrease in resistance. The alignment of the fibres in longitudinal direction, however, decreases electrical contacts in the transverse direction and consequently, increases the transverse electrical resistance. This type of continuous carbon fibre composites could provide gauge factor from −35.7 to −37.6 and from +34.2 to +48.7 in the longitudinal and transverse direction, respectively. Therefore, they can be highly useful for sensing application in civil engineering structures. Carbon fibre reinforced plastic laminates were also found effective in sensing delamination, cracks and different types of damages occurred within the composite structures [26–30].

However, continuous carbon fibre/epoxy composites have low ductility. Nowadays, civil engineers are looking for light weight ductile reinforcements which can replace steel to avoid its corrosion and other problems. For this purpose, hybrid composites have been designed and developed with tailorable mechanical properties. Hybrid composites can exhibit higher breaking strains and ductility due to the so called "pseudo-ductile" behaviour [31]. Therefore, hybrid composites of carbon with other fibres have been investigated for their strengthening as well as self-sensing behaviour [31,32].

Currently existing hybrid composites exhibited continuous strain monitoring capability and can also be used to generate alarm signal well before the breakage of the composites. Both pseudo-ductility and self-sensing behaviours are highly dependent on the properties of the constituent fibres, their proportion and arrangement within the composites. Properly designed carbon fibre-glass fibre (CF-GF) hybrid composites were found to generate vital alarm signal representing the damage occurred in their structure [33,34]. These composites were designed by incorporating an internal carbon fibre core wrapped externally by glass fibre bundle, as shown in Figure 10. These composites showed reliable sensing capability under both monotonic and cyclic loading conditions. A sharp rise in the electrical resistance during the breakage of carbon fibres can be considered as the alarm signal, as shown in Figure 11. It was observed that the load at which the alarm signal was obtained could be designed by changing the relative proportion of carbon and glass fibres. At higher carbon fibre (CF-2.4%, GF-49%), the alarm signal was obtained almost at the breaking load of composites and therefore, these composites were not able to produce warning signal well before the breakage of composites. However, when the carbon fibre was used at lower quantity (CF-0.6%, GF-48% or CF-0.2%, GF-48%), the sharp rise in the electrical resistance was achieved at much lower load than the breaking load, as shown in Figure 11. Therefore, these self-sensing composites can be a suitable candidate for health monitoring of civil engineering structures.

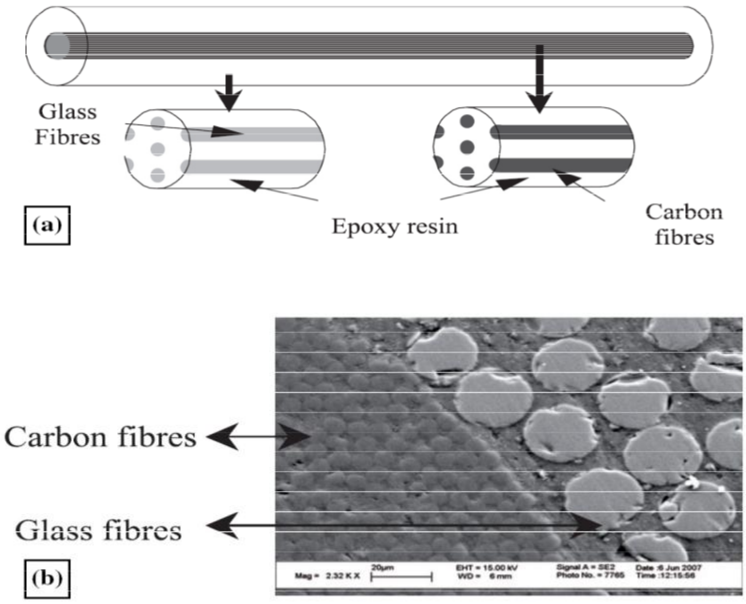

Figure 10. Structure of CF-GF hybrid composite rods for self-sensing: (a) schematic diagram (b) morphology.

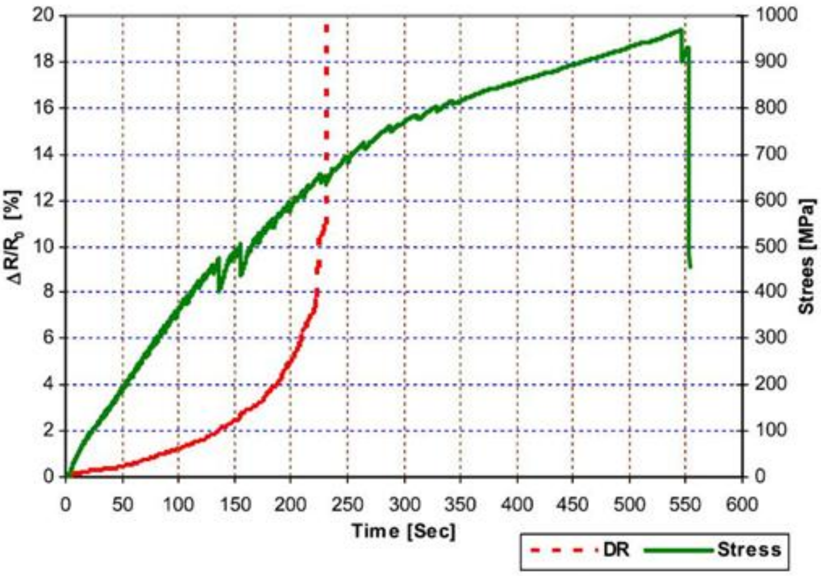

Figure 11. Variation of fractional resistance (dotted line) and stress (solid line) during monotonic tensile testing of CF-GF hybrid rods with CF-0.2%, GF-48%.

However, one of the major drawbacks of CF-GF self-sensing composites is their inability to detect early stage of damage. The change in electrical resistance at low strain (below 0.6%) was found to be only 1%. Good strain sensitivity at low strain through measurement of residual resistance could be obtained for CF-GF composites only in pre-stressed conditions [35]. To overcome this limitation, an innovative composite material with excellent low strain sensitivity has been developed. In this type of hybrid composites, carbon particles were used instead of carbon fibre in combination with glass fibres [36]. Figure 12 shows the schematic of these composites. A fractional change in resistance of 6.2% was obtained at 0.6% strain and therefore, these composites are able to detect early stage of damage. The higher resistance change achieved in this case was attributed to the significant change in the conducting network formed by the carbon particles even at low strain level.

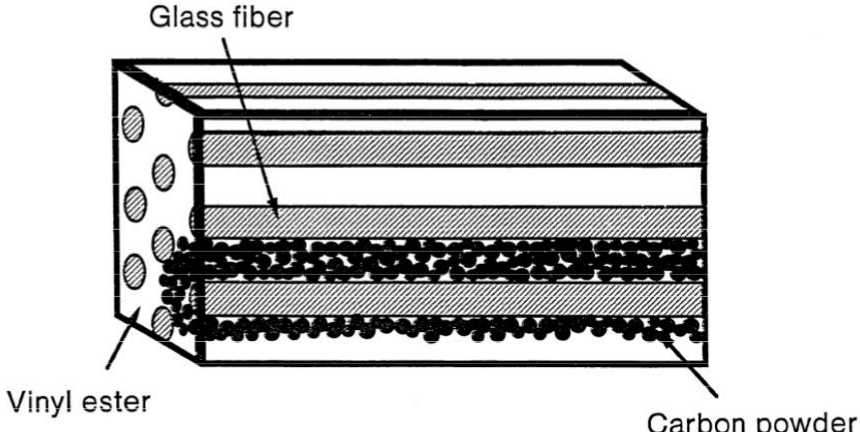

Figure 12. Schematic of CP-GF hybrid self-sensing rods.

Improved strain sensitivity at low strain was also obtained with recently developed carbon fibre reinforced braided composite rods (BCRs) [37,38]. In BCRs, carbon fibres were axially introduced and over-braided using polyester filaments. Carbon fibres were impregnated with a polymeric resin before introducing to the braiding process and the produced structures were cured subsequently to produce the composite rods (Figure 13). The uniqueness of this technique is that the braiding of polyester yarns introduces certain degree of misalignment to the axial carbon fibres. Therefore, the change in the alignment of axial fibres under loading conditions and the resulting change in the electrical contacts lead to substantial change in electrical resistance even at low strain levels. The extent of misalignment introduced in the carbon fibres can be controlled by adjusting the braiding process parameters (such as speed, tension, etc.). Similar to the other sensing composites, strain sensitivity was found better with lower carbon fibre % and the best self-sensing BCR provided a gauge factor of 23.4 at a flexural strain of 0.55%.

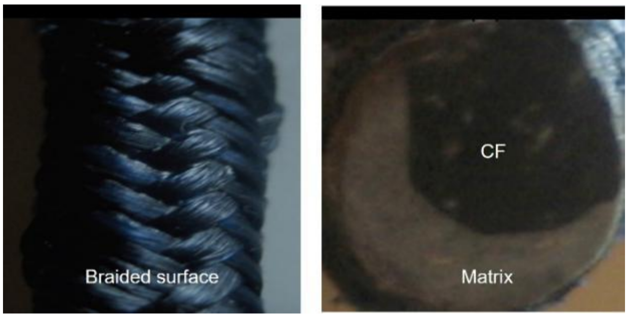

Figure 13. Braided surface and cross-section of BCR.

4.2. Continuous Carbon Fibre Reinforced Concrete Structures

Recently, self-sensing concretes have been developed to detect their own strain and damage using continuous carbon fibre based materials. Smart concretes incorporating carbon fibre textiles (Figure 14a) showed the capability to effectively monitor their strain [18]. Very good correlation was observed between the readings obtained from the textile sensor and conventional strain gauges, as shown in Figure 14b. The difference between the two readings was lower than 5%. The carbon textile based smart concretes provided gauge factor of around 10 and therefore, these smart materials can be advantageously utilized in the construction of self-sensing civil engineering structures.

Hybrid carbon/glass fabric reinforced concrete beams are also able to detect strain and monitor its interaction with a wet environment [39]. An electromechanical sensing with a gauge factor in the order of 1 can be obtained. These smart concrete beams also show detectable correlation between electrical resistance with the load, displacement and strain responses. The wet environment can also be detected by a fractional resistance change in the order of 10^{-5}, which can be detected effectively using the Wheatstone bridge principle.

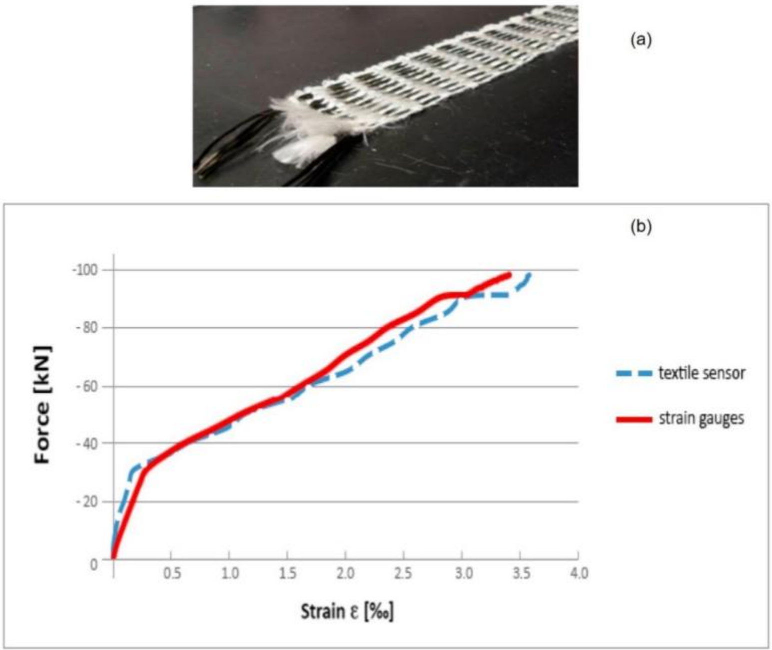

Figure 14. (a) carbon fibre textile for developing smart concrete and (b) correlation between the readings obtained from textile sensor and strain gauges.

V. CARBON NANO MATERIALS BASED SELF-SENSING

CNF and CNT are nanostructures made of carbon atoms. CNF comprises of graphene layers arranged as stacks of cones, plates or cups to create cylindrical nanostructures, whereas CNT comprises of graphene layers wrapped into perfect cylinders. These nanostructures possess outstanding mechanical properties and excellent electrical and thermal conductivities [40]. These characteristics of carbon nanomaterials make them attractive engineering materials for construction applications.

Carbon nano materials can be used for strengthening as well as sensing in construction applications. These nanostructures form conducting networks within the matrix at nanoscale and any change in this network at nano or micro-scale leads to change in the electrical resistivity of the matrix. Consequently, CNT or CNF reinforced composites are able to detect nano and micro-scale damages present in their structure. In addition, changes in the electrical network at very low strain enables the detection of micro strains by these nanostructures.

Different types of mechanical sensors have been developed until today using CNT/CNF or other carbon nano particle (CnP) based composite materials for sensing stress, strain, pressure, and so on. Among them, a few have been demonstrated for civil engineering applications. Nanni et al. [41] developed hybrid self-sensing composite rods consisting of internal conductive core surrounded by an external insulating skin (Figure 15). The conductive core was made of glass fibres impregnated with CnP/epoxy mixture.

This sensing part was shielded by an outer GFRP skin, both to increase mechanical performance and to assure electric isolation. The used CnPs were spherical in shape with an average diameter of 30 nm and 5% CnP was used to produce the hybrid composites with good electrical conductivity. Concrete elements incorporating these hybrid rods exhibited good sensing behaviour, as shown in Figure 16a. The discontinuity in the resistance variation curve at points

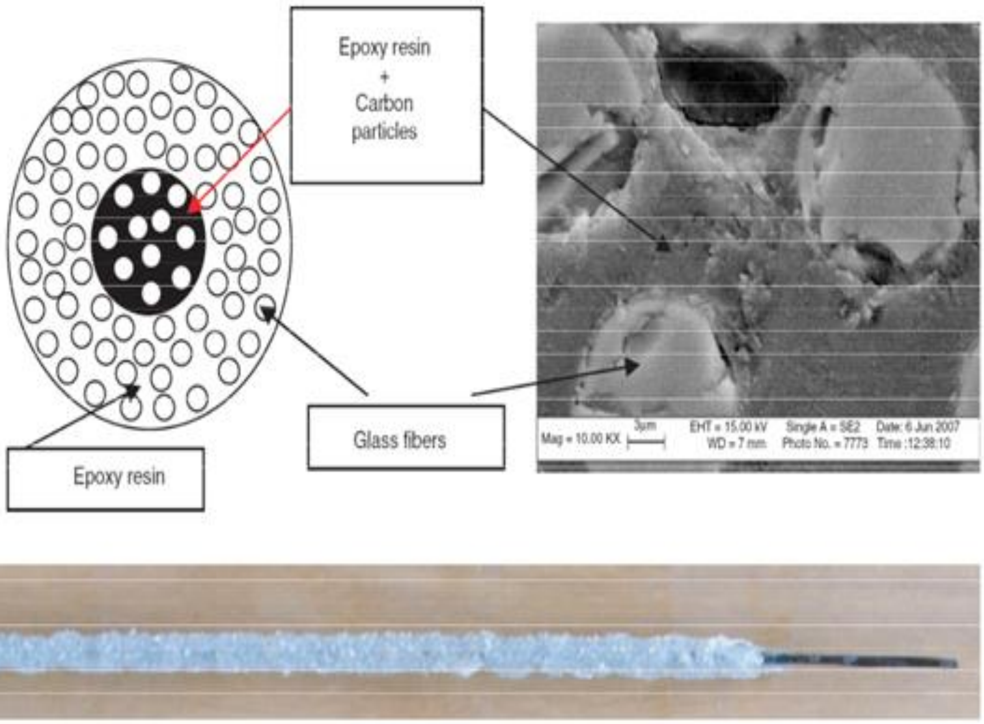

Figure 15. CnP based hybrid composite rods: transverse section scheme, SEM micrograph, and longitudinal view.

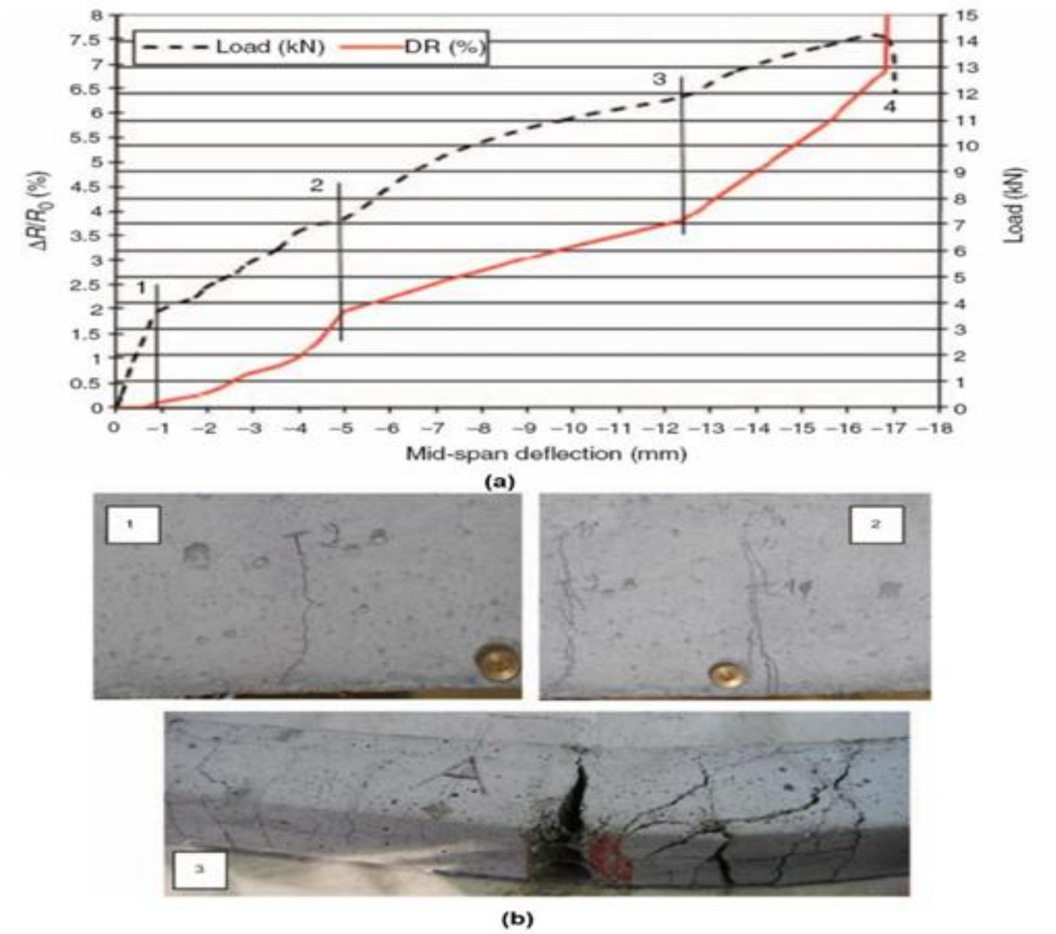

Figure 16. Self-monitoring performance (a) and cracking pattern (b) of concrete specimens.

1, 2 and 3 represented various changes occurring in the concrete specimens such as initial concrete cracking (point 1), formation and propagation of additional cracks (point 2) and severe cracking and failure of concrete specimens (point 3), as shown in Figure 16b.

Self-sensing ability of CNF reinforced concrete has also been reported [42]. Under compressive strain, electrical resistance variation up to 80% was obtained using the most conducting nanofibers at 1 vol.% concentration. The strain monitoring capability of CNF/concrete specimens was observed to be highly dependent on the type, conductivity and concentration of CNF and optimum conditions resulted in strain sensitivity suitable for practical applications.

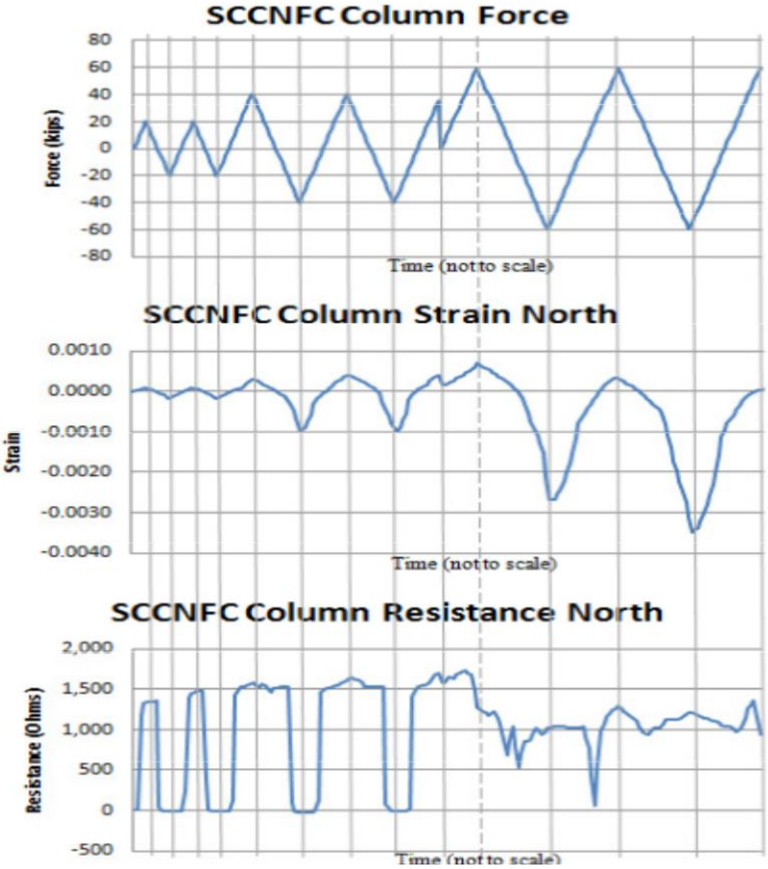

Figure 17. Electrical resistance variation with force and strain of CNF reinforced concrete.

Under reverse cyclic loading also, CNF reinforced concrete showed good strain and damage sensing ability [43]. At smaller strains, the peaks and valleys in the electrical resistance of CNF reinforced concrete matched well with that of the applied force and the strain in the concrete, as shown in Figure 17. However, when the strain became high and the specimen was severely damaged, no correlation was observed between the electrical resistance and strain/force and electrical resistance increased quite irreversibly. This change in electrical resistance pattern indicated the occurrence of damage in the concrete specimens.

Hybrid cement composites of CNTs and carbon fibres (Figure 18) also exhibit good sensing behaviour [44]. In these composites, 1 vol% of multi-walled CNTs was used in combination with 15 vol% of carbon fibres. Under cyclic compressive loading, the changes in electrical resistance could mimic both the changes in load and strain with high reliability. However, the response was nonlinear and rate dependant. Nevertheless, for a particular loading rate, the strain in the developed materials could be predicted from the fractional change in resistivity using a non-linear calibration curve. As compared to only carbon fibre sensor, hybrid sensor exhibited better results with good repeatability. This can be observed from the lower scatter of FCR values in case of hybrid sensors than the carbon fibre sensor, as presented in Figure 19.

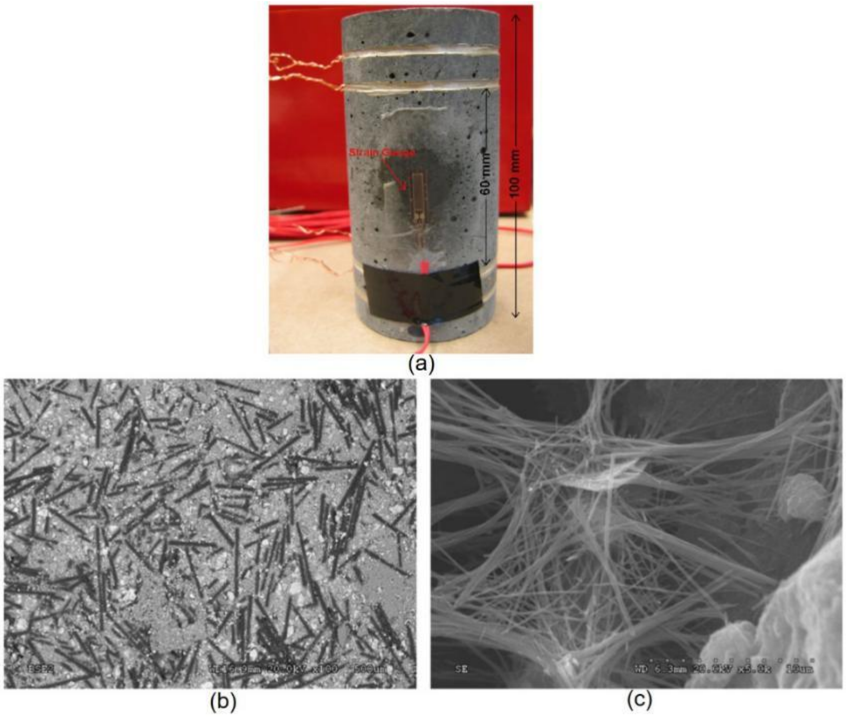

Figure 18. CF-CNF hybrid cement composite (a), CF distribution within cement (b) and MWCNT within the cement hydration product (c).

Recently, CNT/cement composite sensors were developed and demonstrated their application in pavement monitoring [45]. For this purpose, carboxyl functionalized CNTs were dispersed within cement using ultrasonication process with help of a surfactant (sodium dodecyl benzene sulfonate). At 0.1% MWNT concentration, very good sensing behaviour was achieved, as shown in Figure 20. These CNT sensors were installed in the road for testing the pavement monitoring capability (Figure 21). Figure 22 shows the response of pre-cast and cast-in-place CNT sensors while a truck passes over the road and compares the response with that obtained in case of strain gauges. It can be observed that an abrupt change in voltage occurs when a wheel passes over the road and each wheel represents one signal peak. As compared to the signals obtained with the strain gauges, the CNT/cement sensors showed higher detection accuracy, as some signals were missed in case of the strain gauges.

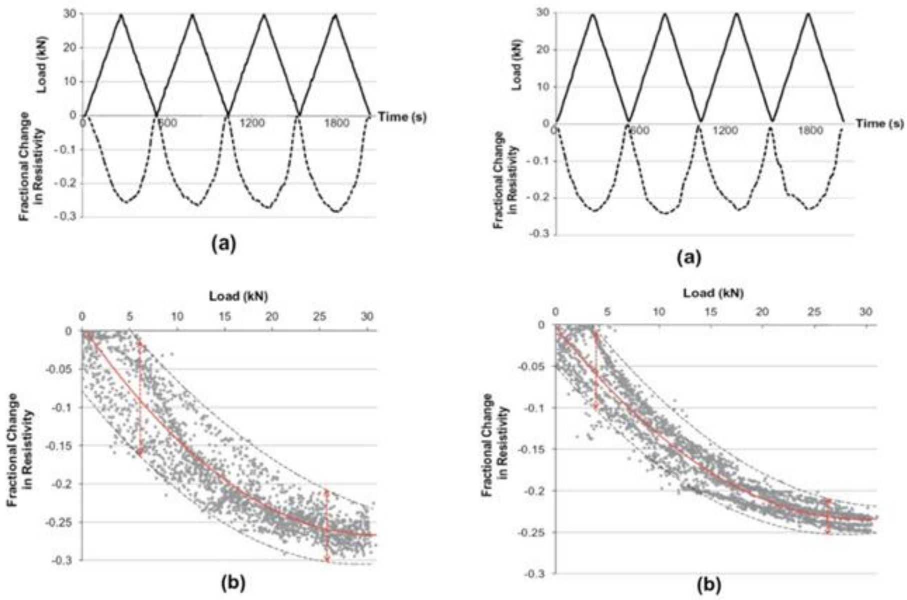

Figure 19. Change of FCR with load for CF concrete sensor (left) and hybrid concrete sensor (right).

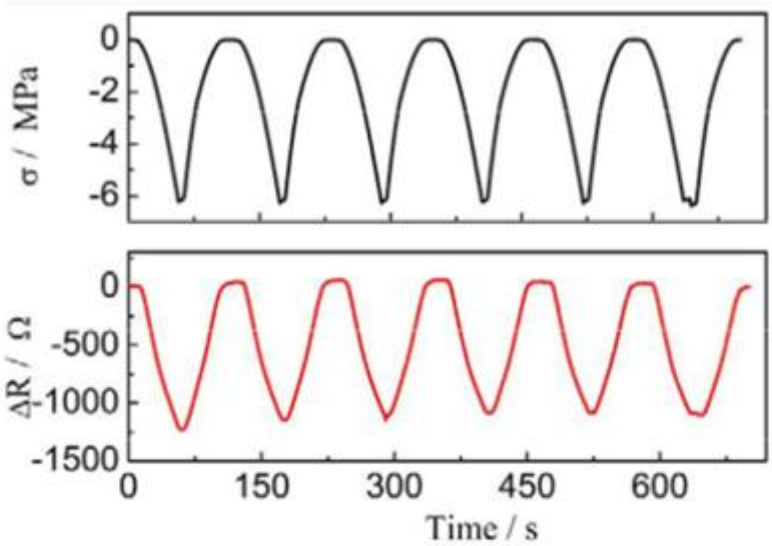

Figure 20. Sensing performance of CNT/cement sensor.

Figure 21. Installation of CNT/cement sensor in roads for testing monitoring capability.

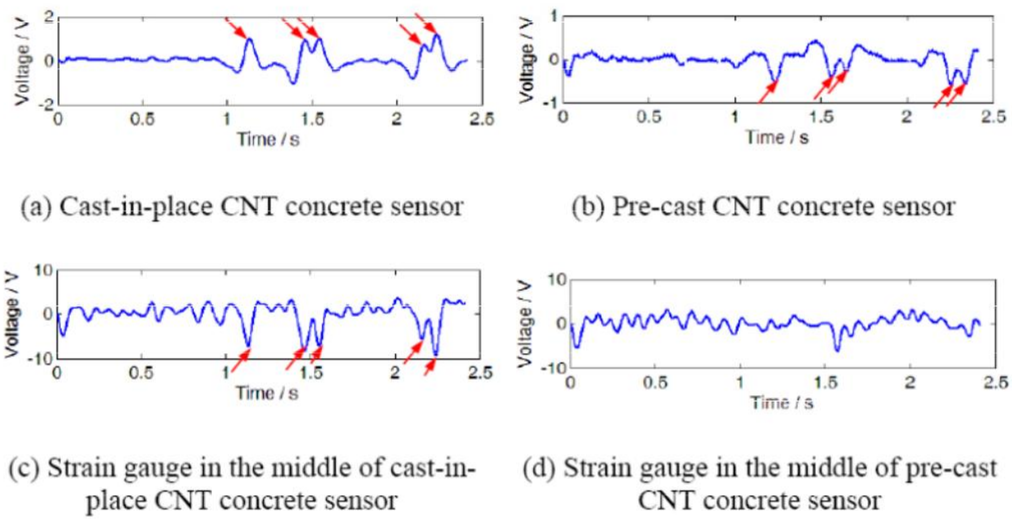

Figure 22. Response of cast-in-place and pre-cast CNT sensors (a, b) and strain gauges (c and d), while a truck passes over the road .

Self-sensing hybrid polymeric composites have also been developed using CNT. These composites are commonly known as multi-scale composites as they are fabricated combining macro and nano scale reinforcements [46–49]. The conventional macro-scale reinforcements (such as glass, carbon, etc.) are used for the strengthening purpose, whereas CNTs are incorporated to achieve sensing behaviour. In addition, CNTs can also improve mechanical properties of these composites. As compared to other hybrid composites, one major advantage with CNT based multi-scale composites is that they can detect micro-scale damages in the composite structure [50]. This is possible as damages even in nano and micro-scales can alter the conducting network of CNTs, resulting in change of resistivity of the composites. Figure 23 shows the sensing behaviour of a CNT based multi-scale braided composites.

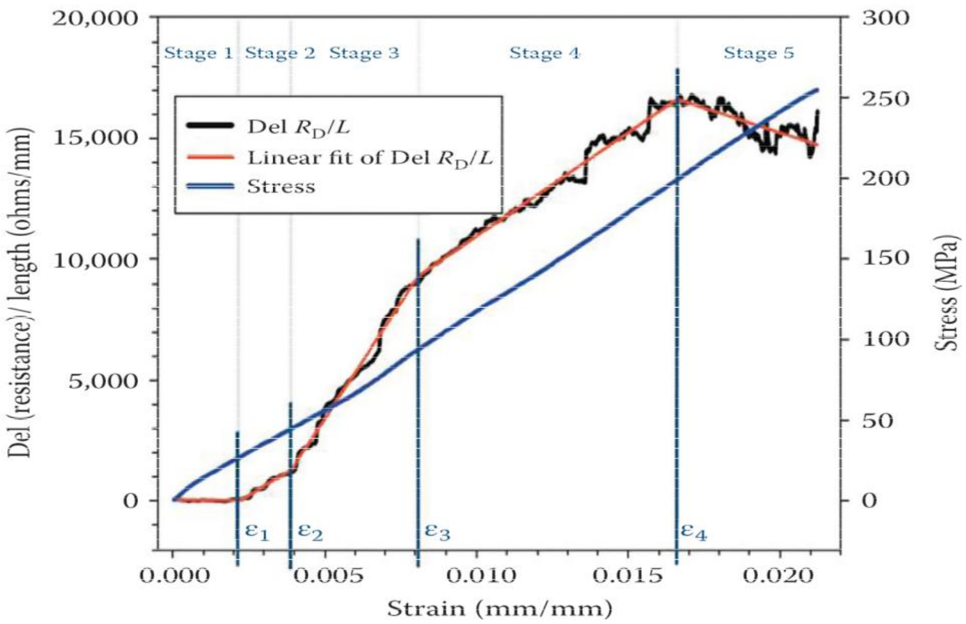

Figure 23. Change of electrical resistance with strain in multi-scale 3D braided composites.

It can be observed that the change in the slope of the resistance curve represents different types of damages in the composites. The microscale damages such as transverse cracks or micro delamination starts at stage 2 and accumulates in stage 3, resulting in considerable increase in the electrical resistance change. In stage 4, the saturation of micro-damages occurs and they close due to Poisson's contraction and jamming of yarns in stage 5.

Braided composites using continuous CNT yarns have also been developed for developing self-monitoring systems [51]. These advanced braided composites have huge potential for application in structural applications. Braided composites present tailorable mechanical properties and surface characteristics and have been demonstrated as very good strengthening materials of concrete or masonry structures [52–55]. Therefore, sensing braided composites can be extensively utilized for both strengthening and health monitoring of civil engineering structures.

VI. CONCLUSIONS

In this paper, an overview of carbon composites developed for health monitoring of civil engineering structures is presented. Carbon materials in different forms such as short fibre, particle, tows, fabrics and nanomaterials have been extensively studied for developing health monitoring systems. They have been either directly incorporated within cementitious materials for developing smart concrete or have been incorporated within polymers to fabricate self-sensing composites. Self-sensing polymeric composites can be advantageously utilized for strengthening as well as health monitoring of civil structures. Hybrid composites of carbon with other fibres offer the possibility of achieving higher ductility and generating alarm signal well before the composite's failure. Therefore, they are useful to avoid sudden collapse of structures. However, they are not capable of detecting early stage damages in the structures. The low strain sensitivity of carbon composites can be greatly enhanced by using carbon nanoparticles, nanofibers or nanotubes. Formation of conducting networks at nano-scale offer them the possibility to detect very low strain and micro-damages in the structures. Smart concretes incorporating carbon nanomaterials also exhibit very good sensing performance. However, although carbon based self-sensing materials offer huge possibility to develop effective health monitoring systems, there exists a few critical issues which need to be solved in near future. More research and developments are required to develop self-sensing systems which can identify the location of damage. Although carbon nanomaterials based self-sensing materials offer better sensing performance, they are expensive and have processing difficulties. Enough information is also not available in the existing literature on the effect of environmental and usage conditions on the self-sensing performance of the developed composites. Therefore, for practical application of carbon based SHM systems, further research work is extremely essential for overcoming the practical problems in implementing these systems and reducing the cost and improving affordability of these materials.

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