Nano-composite sensors for smart textile composites

Saad Nauman, MS & E department, Institute of Space Technology, Islamabad, Pakistan & King Abdullah University of Science and Technology (KAUST), Physical Science and Engineering Division, COHMAS Laboratory, Thuwal 23955-6900, Saudi Arabia

Gilles Lubineau, King Abdullah University of Science and Technology (KAUST), Physical Science and Engineering Division, COHMAS Laboratory, Thuwal 23955-6900, Saudi Arabia

Abstract

Textile composites are an emerging class of materials pulled by the emerging demand in wearable electronics. These composites employ some aspect of textile technologies in their fabrication, ranging from fiber placement techniques such as weaving and knitting to various coating practices such as printing or dyeing. Contrary to most of structural composites that employ fibers in various forms and types as reinforcement, smart textile composites mainly take advantage of exceptional properties of nano fillers, both carbonaceous and non-carbonaceous. These fillers can be used to create reinforcement network with exceptional properties even at very low filler concentrations. These fillers have not only been employed to improve mechanical properties but have also been incorporated for their exceptional electrical and thermal conductivities. These latter attributes have been successfully exploited for the development of smart composites capable of sensing changes in their environment.

Keywords: *Sensors, Smart Textiles, Smart Composites, Self-Sensing Composites, Nano Composites*

Introduction: Smart or intelligent structures are those which are either solely capable of sensing changes in their environment or have the dual functionality of not only detecting various stimuli in their environment but are also able to respond to these changes in their environment. The former class of smart structures are sometimes referred to as passive smart structures whereas the latter are termed as active smart structures [1]. This is because of the fact that passive smart structures can only ‘sense’ whereas active smart structures can ‘sense and actuate’ [2]. The passive smart structures are capable of sensing various conditions during the service life such as strain, loads, temperature and pressure etc. The so called active smart structures are capable of adaptive actuation such as changing shape, color, temperature or inner stresses etc.

The recent trend in all the engineering domains is geared towards the development of smart structures with integrated sensors because of their inherent ability to provide information about their structural integrity in real time. Like many engineering feats of the past this paradigm is inspired from living bodies [3]. The animal and human bodies have an integrated network of sensors which continually detect changes in various environmental factors such as temperature, humidity, load and strain etc. The data emanating from the sensing arrays is transmitted to central nervous system via neural network. The information is processed and interpreted to assess the extent of threat or damage and a decision is made regarding necessary actuation mechanism to be invoked. The actuation mechanism generally involves muscular action in the form of various bodily movements. In the similar vein, the critical engineering structures such as aircrafts, bridges and wind mills etc. are being proposed with inherent smart features

in order to ascertain their smooth functioning and safe operations. The proposed approach has multiple advantages as against traditional approaches. It is evident these structures will allow operational managers and maintenance engineers to avert economic losses and casualties by allowing early detection of onset of damage and any threats to the structural integrity. The so called 'scheduled maintenance' paradigm requires the engineering structure to be put out of service and inspected using various NDT techniques before being repaired and overhauled if needed to put it in service once again. This process involves extra cost of putting the structure off service and investigated. The scheduled replacement of various parts after completion of a given number of working hours also entails extra cost of part replacement. The alternative approach of making structures self-sensing would make them self-reliant as far as their operational safety is concerned. This would reduce the maintenance cost and would allow keeping the structure operational as long as its structural health is sound without resorting to scheduled maintenance. For many critical structures, this would enhance safety and operational security in addition to enabling continuous uninterrupted services.

Composite materials are inherently synergistic in nature where two phases; the reinforcement and the matrix, are combined to complement one another. This provides a unique opportunity of designing inherently smart structures using composites. Smart composites can have one of the two phases i.e., either the reinforcement or the matrix, with the sensing or actuation capability thus allowing smart functionality. An excellent example is the case of structural carbon fiber reinforced composites that are made of an assembly of continuous carbon fibers inside a polymeric matrix. The fibers ensure the mechanical performance, but also confer the composite with some electrical conductivity as they are by nature conductive and form a conductive network. The variation of this network, either due to mechanical stretching or to degradation of the materials, results in a change of the electrical properties (here, piezo resistivity), that can be used for doting the material with a self-sensing capability [4].

Textile technologies, owing to their inherent versatility are being explored to manufacture a variety of reinforcement architectures. The main attraction that these technologies offer are continuous fiber placement at precisely predetermined angles allowing various innovative design features to be incorporated and experimented with. Added to that is the prospect of using high performance filaments or tows bestowing the composites with higher failure strains and multiple energy dissipation mechanisms allowing greater fracture toughness. There is also a possibility to tailor reinforcements with through the thickness reinforcing filaments/tows thus allowing suppression of interlaminar shear often described as the Achilles' heel of the composites [5]. In most of the cases these reinforcements can be manufactured by incorporating little or no modifications to the traditional textile processes thus allowing manufacturing of innovative reinforcement architectures at minimal cost [6]. Moreover the continuous nature of various textile manufacturing techniques make reinforcement manufacturing a low cost endeavor amenable to large scale industrial production. As mentioned earlier, these technologies also allow designing of an unlimited variety of reinforcement architectures by altering the motifs and/or filaments/yarns involved in making these reinforcements. For composites this turns into unprecedented designing for composite manufacturers and designers.

In structural composites primary reinforcement materials are fibrous in nature. Fibers both in chopped and filament forms bestow easy formability, high aspect ratios and tailor-ability of properties. Fibrous

reinforcements can be classified into continuous or discontinuous. The continuous reinforcements can be further distinguished into 1D, 2D, 2.5D and 3D reinforcements. With the exception of 1D reinforcement, the latter three can be manufactured using traditional weaving technologies with little or no modifications.

The 2D reinforcements have multifilament tows woven in interlacing patterns in a planar fashion using classical weaving technology. These reinforcements are generally woven in plain, twill or satin weave patterns or their variants but the interlacing tows remain in planar configuration. These reinforcements can be used to manufacture laminated composites but with limited interlaminar shear strength as through-the-thickness direction remains unreinforced and the laminae are only held together by the matrix. 2.5D reinforcements are unique in the sense that they are manufactured using traditional weaving techniques but unlike traditionally woven reinforcements these have different layers 'interlocked' together using multifilament tows [7-9]. The thickness i.e., the laminae interlocked together are only limited by the number of frames installed on the weaving loom. Since these reinforcements have through-the-thickness reinforcing tows which bind different layers (laminae) together, they have exceptional interlaminar shear strength and are largely delamination resistant. Unlike 2.5D reinforcements, the 3D reinforcements are manufactured on custom designed weaving looms where through the thickness multifilament tows are interlaced much like the planar tows in traditional weaving technique. The interlacement in the 3rd dimension or z-direction requires redesigning and alteration of the traditional weaving process and hence the term 'truly 3D woven reinforcements' is also sometimes used for these reinforcements. In addition to these techniques another type of reinforcement has been proposed namely Non Crimped Fabrics (NCF). These are closely related to textile reinforcements as the manufacturing technique bears resemblance to traditional weaving where two or more group of filaments are employed for interlacement but since the multifilament tows are placed over one another without interlacing them which results in lack of waviness or crimp in the resulting reinforcements these have been called non-crimped fabrics.

Owing to their exceptional through-the-thickness properties and tailorability afforded by unlimited weaving architectures which can be designed for particular applications, textile reinforcements have found wide applications in structural composites. Wide assortment of high performance fibers, ranging from E and S glass to para-aramid and carbon can be used to weave various types of 2D, 2.5D or 3D reinforcements [10, 11].

The above materials are mainly based on continuous fibers, which bear the main load and provide the mechanical strength and stiffness. More recently, a number of nano materials have also be incorporated in order to make Nano composites [12].

Nano-composites are a class of composites that can be fabricated by employing various types of nano-fillers ranging from so called 0D, 1D to 2D configurations in various concentrations in matrix materials [13]. Generally these fillers are used to enhance certain secondary properties such as thermal [14] or electrical conductivity [15], UV stability [16], bulk and color [17] or ameliorate mechanical properties [18-20] such as hardness [21], toughness [22], tensile [23], compressive [24] and interlaminar shear strength [25] etc. In the latter case these fillers are often used as additives along with fibrous reinforcements which

predominantly perform the function of primary reinforcing phase whereas the nano-fillers as additives alter the matrix properties allowing it to better transmit loads towards the reinforcement, strengthening interface and bridging micro cracks thus playing a supportive role alongside the primary reinforcing and the matrix phases.

When incorporated as secondary reinforcement, these fillers ought to have exceptional mechanical properties and high aspect ratios which endow them superior reinforcing properties at much lower proportions [26]. Such elevated mechanical properties are offered by various allotropic forms of carbon such as fullerene (0D), carbon nanotubes (1D) and graphene (2D). Owing to their exceptionally high aspect ratios [27], carbon nanotubes have found wide applications as secondary reinforcing phase where they have been found to effectively improve interfacial interaction [28], bridge cracks [29] and enhance toughness by affording a meandering path for crack propagation [30]. However, we should highlight that the incorporation of nano particles inside a structural composite does not always result in an improvement of the mechanical properties. It might also happen that the introduced particles promote the development of defects and reduce the effective mechanical properties of the final composite structure [20]. On the other hand fillers such as conductive metallic nano particles i.e., gold [31] or silver [32] and all the allotropic forms of carbon [33] and silica [34] have been used to incorporate secondary properties in the host composites. Indeed, ensuring multifunctionality, such as specific electrical, piezo electrical or thermal properties is probably the main advantage of using nanoparticles as such features can be obtained at very low volume fraction depending on the efficiency of the introduced particles in creating a percolated network [35]. Conductive metallic nano particles have been found to incorporate exceptional conductivities and gauge factors (sensitivity) in the matrix materials thus allowing them to be used as strain and pressure sensors [36]. In the similar vein, carbonaceous nano fillers have also been used to incorporate electrical and thermal conductivities in composites. Their use has been reported to endow the composites with conductivity essential for suppressing static charges in structural composites [37] and when the concentrations are maintained at a percolation threshold the composites have been reported to demonstrate gauge factors much greater than the traditional strain gauges [38]. This latter property has been widely exploited for in-situ strain and damage sensing in composites [39-46].

In composites both the primary and secondary reinforcements are used with either thermoset matrices such as epoxies, unsaturated polyesters, vinyl esters and phenolics or thermoplastic matrices such as polyetheretherketone (PEEK), polyethersulphones (PES), polypropylene (PP) or polyimides (PI) etc.

In making smart nanocomposites, various approaches have been exploited. Firstly, matrices can be modified by adding nano fillers to these such as carbon nanotubes, graphene or carbon nano-particles. In addition to enhancing mechanical properties of these composites, the exceptional conductivities of various allotropic forms of carbon can render them conductive thus forming a percolation network of conductive fillers in the matrix material. When these filler concentrations are maintained at the percolation threshold, the percolation networks become exceptionally sensitive to the applied strains thus allowing self-sensing of the composites. These approaches have been used for structural health monitoring of composites [47].

Secondly, the nanocomposite filaments can be manufactured by incorporating conductive fillers in the polymer and then extruding the filament [48] [49] or by doping the filaments or yarns with the nano fillers [50, 51], filaments or yarns with intrinsic sensing capabilities can be manufactured. These filaments/yarns can be woven into textile reinforcements much like traditional yarns and filaments. Once integrated in the composite, these filaments are capable of detecting structural health with greater fidelity as they become an integral part of the reinforcement when inserted during weaving.

Yet another approach consists in printing the nano-composite coating onto the surface of composite components using traditional printing technologies [52]. This approach though does not give information about the failure mechanisms operative inside the composite but can still be employed as an alternative to resin bonded metal foil strains gauges because of its simplicity, ease of application and inherently superior sensitivities of nano-composite coatings.

Owing to the intrinsic hierarchical nature of textile reinforcements, whereby microscale fibers constitute meso scale tows which are interlaced to form macroscale reinforcement [53], conductive fillers can be integrated at various scales ranging from micro to macro in order to design composites with self-sensing capabilities. This results into the fabrication of nano-composite filaments/yarns and reinforcements which can be directly used for manufacturing smart composites. The approach helps avert an extra step of integrating sensors inside or on the surface of composites with an added advantage of greater sensing fidelity on the part of sensors which become an integral part of the composite and undergo the similar fabrication and in service stresses as the other components of the composite.

In the following numerous approaches which take advantage of hierarchy in textile composites to manufacture smart composites have been highlighted.

Micro-scale Integration - Extruded composite thread sensor for strain sensing applications: Asfar et al. [54] have reported an innovative extruded-coating method for developing thread sensors coated with conductive polymer composite (CPC) solution. Carbon nanoparticles (Printex-L6) were dispersed in thermoplastic polystyrene matrix using ultrasonic disperser. The resulting CPC was used to coat cotton threads using the extruded-coating process specially developed for the purpose. The threads obtained after the deposition of CPC are composite in nature. The manufacturing technique results in the formation of core-sheath structure of the sensor. The bulk of the coated material was found to be deposited on the surface with some of the material penetrating sub-surface layers in the intra yarn interstices. The SEM micrographs also revealed that a concentration gradient of the CPC from the surface to the core existed in the composite threads. This resulted in the formation of multiple percolation networks all along the thread. The hybrid nature of the manufacturing process adopted, which combines the features of extrusion and coating, to manufacture composite threads results in rapid and reliable deposition of CPC solution on the targeted substrate. Extruded-coating also allows altering the process parameters as well as the substrate and the constituents of CPC solution to tailor a range of sensing properties in the composite sensors. In order to demonstrate the usefulness of the extruded-coating process for the fabrication of composite sensors, a cost effective cotton yarn was selected as the substrate material. The CPC solution comprising of polystyrene matrix and carbon nanoparticles resulted in a thread sensor with gauge factor of 15.5 whereas traditional metal foil strain gauges are reported to have gauge factors ranging from 2-5.

The substrate material is not only biodegradable but the thermoplastic matrix used is also recyclable. This choice of the substrate and CPC matrix endow the sensor CO₂ neutrality as one of the constituent originates from the plant resource. The extru-coated thread sensor specimens were attached at the extremities with copper wire with the help of silver conductive paint supplied by RS components. These specimens were tested on universal testing machine (UTM) in quasi static mode at a crosshead speed of 5 mm/min. The tests were conducted in traction mode on a gauge length of 10 cm. Cyclic loading was also applied on similar test specimens for up to 10 loading cycles. These tests helped determine various sensor performance parameters and errors. A commercially available data acquisition module (KUSB 3100) in conjunction with an instrumentation amplifier (INA 118) were used for data acquisition, linearization and amplification (Figure 1). The thread sensor was connected in Wheatstone bridge configuration with the other known resistances. This set-up comprising of analog to digital converter, amplifier and Wheatstone bridge connected to a PC allowed retrieval and observation of sensor data in real time. The INA 118 enabled real time amplification of the acquired data thus facilitating its observation for sensor performance analysis during the aforementioned tests.

Figure 1: Schematic of the data acquisition system [6]. © [2016] IEEE

The SEM analysis revealed an elliptical cross section of the threads fabricated through extru-coating (Figure 2). These images show the core fibers surrounded by the CPC. The manufacturing technique ensures that the bulk of the solution adheres to the surface with the core remaining largely unaffected.

Figure 2: (a) SEM image taken on the elliptical cross-section of the extru-coated thread (SEM Magnification: 175X). (b) Fibers in the extru-coated thread core surrounded by the thermoplastic matrix (SEM Magnification: 500X). (c) Fibers in the extru-coated thread core surrounded by the thermoplastic matrix (SEM Magnification: 1.70 KX). (d) Fibers in the extru-coated thread core surrounded by the thermoplastic matrix (SEM Magnification: 4.98 KX) [6]. © [2016] IEEE

The tensile test results obtained on thread sensor specimens were plotted as shown in Figure 3. The dynamic range determined from monotonic tensile tests was approx. 11 %. This range is largely a function of the mechanical properties of the substrate, the thermoplastic matrix used and their mutual interplay as the coated thread sensor structure is akin to that of a laminated composite.

a)

b)

Figure 3: a) Stress vs. strain and b) Normalized resistance vs. strain plot for the representative sensing thread [6]. © [2016] IEEE

Similar loading conditions were used to conduct dynamic tensile tests on the thread sensor specimens for up to 10 cycles (Figure 4).

Figure 4: Normalized resistance against strain for the smart sensing thread during cyclic loading (10 cycles) [6]. © [2016] IEEE

Regression analysis of the best linear fit of the data revealed a sensitivity or gauge factor of 15.506. The hysteresis in the sensor output caused the Integrated Non-Linearity error (INL) to increase with the number of cycles (Figure 5). It was maximum for the tenth cycle during unloading reaching 24.8% of the FSO (Full Scale Output).

Figure 5: Bar graph of % integrated non-linearity error for all cycles [6]. © [2016] IEEE

The underlying mechanism dictating the change in resistivity with applied deformation and hence the sensitivity of the thread sensor is based on percolation theory. As mentioned earlier, the extru-coating

process results in core-sheath structure with the surface receiving maximum CPC concentration. Some of it is adsorbed at the surface, the rest gets absorbed with the core receiving minimal solution ingress. The tensile loading caused the percolation networks formed by the conductive nano-particles (CNPs) to disturb and alter. The increasing load causes these particles to get distant, the micro-cracks also causing the networks to breakdown and resulting in an overall increase in electrical resistance. The cotton fibers spun to form the thread sensor get unfurled with increasing load, this also causes the percolation networks to get altered as some of the material is adsorbed on these fibers with the remainder going inside the interstices. All of these mechanisms lead to increased sensitivity in the thread sensors. The fracture is indicated by the sudden rise of resistance to infinity in the normalized resistance vs. strain plot (Figure 3-b). Figure 6 shows core fibers after the failure of the thread sensor. The white cotton fibers protruding from the fracture surface attest to the fact that the core receives minimal CPC solution.

Figure 6: Extruded thread specimen mounted on the UTM after the test; Inset shows protruding fibers from the fractured edge [6]. © [2016] IEEE

The versatility of the manufacturing process would allow use of a number of different substrate materials including yarns and filaments, matrices and various different types of nano-fillers such as carbon nanotubes (CNTs) and graphene nano platelets (GNPs) etc. This would not only allow tailoring the gauge factor (sensitivity) of the resulting sensor but would also enable design of a sensor with specified dynamic range for a particular application. Owing to a large spectrum of properties which can be achieved in this way, these extruded nano-composite sensors are destined for applications in smart self-sensing composites for their online in-situ SHM, smart textiles for monitoring various physiological parameters, robotic arms, artificial limbs, artificial skins and intelligent prosthetic limbs etc.

Let us also mention that the core-sheath structure can be obtained by simply dipping of the fabric 1D thread inside a suspension of nanoparticles. Using simple dipping techniques, Lubineau et al. [51]

introduced a concept of functional smart fiber capable of measuring with only two electrical connections at each end of the fibers, both the amplitude and the location of an applied force (Figure 7). The idea is based on the interweaving of two functional fibers with well-designed piezoresistive properties. For the first fiber, a uniform coating of nanoparticle is deposited over the whole length by a uniform dipping. This fiber provides then a similar response wherever the load is applied and provides the scale-up for the load measurement. The second fiber is equipped with a piezoresistive coating with a gradient of gauge factor. The combination of information from both fibers makes possible to localize and measure the force with a minimum number of wires.

Figure 7. Fabrication of double-twisted smart threads (DTST). a) A schematic diagram illustrating the fabricating process of DTST and b) digital images of a homogeneous treated thread (HTT), a gradient-treated thread (GTT), and a DTST. c) SEM images of graded-thickness SWCNT coatings on GTT at P3, P6, and P9. SEM images of d) a high-magnification image of the SWCNT coating and a lower magnification image of e) the homogeneous SWCNT coating on HTT before and after coating with PVA.

Reprinted with permission from John Wiley and Sons, Extracted from [51]

Meso-scale integration- laminated smart composites: Nauman et al. [55] prepared a CPC solution as described earlier and applied it on three different substrates; spun cotton yarn; 71 Tex, polyethylene monofilament; 48.2 Tex and polyamide monofilament; 25 Tex. It was found that the coating was more uniform and homogeneous for synthetic filaments because of the absence of interstices and pores. A total of 12 samples obtained from three types of coated substrates were then subjected to the measurement of electrical resistance using a Multimeter. The resistivity values were then calculated from the fineness,

length and electrical resistance values. A comparison of the electrical resistivity values for the three variants is presented in Figure 8 [55].

Figure 8: Resistivity values calculated for different substrates coated with 35 wt. % carbon black solutions [55].

It was found that polyethylene had more uniform resistance values because of its homogenous coating. The coated yarns and filaments were then subjected to quasi static tensile tests on MTS ½ Tester at a crosshead speed of 5mm/min. The electrical resistivity was measured using a voltage divider circuit and Keithley KUSB 3100 data acquisition module. As a result of optimization experiments, polyethylene substrate based sensor was employed for designing a filament sensor. In order to further tailor the electrical resistance, two ply polyethylene was employed, the two extremities of which were attached to fine copper wires with the help of silver conductive paint (RS components). This helped obtain robust connections with minimal voltage drop. The technical data for the designed sensor is summarized in Table 1.

Table 1: Double ply polyethylene filament based sensor [55].

Parameter	Value
Average linear density of the filament (g/km)	48.23
Average diameter of the filament (mm)	0.7
Average width of the sensor cross section (mm)- across major axis	1.68

Average thickness of the sensor cross section (mm)-across minor axis	1.26
Aspect ratio of the sensor (width/thickness)	1.33
Length of the sensors (cm)	11.7
Initial resistance of upper sensor (k Ω)	34
Initial resistance of lower sensor (k Ω)	24

These filament sensors were subjected to two types of tests prior to their insertion in the composite. The first one was monotonic quasi static tensile test up to 2.75% strain. The other one was cyclic loading test on the similar tensile test fixture. Both the tests were performed on MTS 1/2 Tester at a constant crosshead speed of 5 mm/min. The normalized resistance and stress for both the tests have been plotted against strain in Figure 9- a & b.

Figure 9: Normalized resistance and stress plotted against strain for sensor outside composite. (a) Tensile test up to 2.75% elongation; (b) Hysteresis 10 cycles at 0.5% extension [55].

The monotonic tests reveal remarkable linearity in the sensor response. The fidelity with which normalized resistance follows the stress-strain behavior of the sensor can also be observed. The cyclic test reveals hysteresis in the sensor response which gradually decreases with increasing number of cycles ultimately becoming negligible for the tenth cycle.

In order to validate the sensor performance for use in composites for their SHM (structural health monitoring), plain woven 2D reinforcements were woven using glass tows on a conventional weaving loom. The reinforcement specifications are summarized in Table 2.

Table 2: Reinforcement specifications [55].

Parameter	Value
-----------	-------

Linear density of warp tow (Tex)	2331
Linear density of weft tow (Tex)	2331
Average thickness of reinforcement (mm)	0.8
Warp tows density (tows/cm)	18
Weft tows density (tows/cm)	16
Areal weight (g/m ²)	789
Fiber volume fraction (%)	60

Five layers of the reinforcement were laid up over one another with all the warp and weft directions placed directly over one another. Two filament sensors were placed between 1st and 2nd & 4th and 5th layers to detect compression and traction respectively in the top and bottom of the composite specimens during 3 point bending tests. TexGen generated geometry of the laminated composite is shown in Figure 10.

Figure 10: TexGen generated geometry of 2D reinforcements placed over one another having two sensors at the top and bottom [55].

The lay-up was impregnated using vacuum bag infusion process. Resin employed was a low viscosity high performance epoxy Epolam 5015. The sensor connections were carefully protected from resin by isolating these in a sub mold. The curing of the resin in the mold was followed by post curing in a vacuum curing oven for 6 hours at 80°C. The completely cured composite sheet was then cut into specimens of 12 cm X 3cm dimensions for 3 point bending tests.

The specimens were loaded on Instron 1185 test bench installed with 3 point bending test fixture in order to conduct monotonic tests until complete fracture of the specimens. These tests were conducted at

constant crosshead speed of 1 mm/min. A typical Force-displacement plot against normalized resistance output for the top and bottom sensors is given in Figure 11.

Figure 11: Force-displacement plot against normalized resistance for the two sensors inside laminated composite specimen tested until fracture [55].

The normalized resistance plots for the top and bottom sensors follow the deformation pattern and failure events in the composite undergoing compression and traction. Cracking of the composite lamina and delamination events are represented by kinks in the lower sensor response. The fracture of the lower composite layers coincides with the sensor failure whereby its resistance suddenly jumps to infinity. This fracture event can be detected by sharp drop in load. The upper sensor is also capable of detecting delamination and ply failures with each kink in its response coinciding with snarling force-displacement curve. The upper sensor however does not experience complete fracture and remains intact as its resistance does not jump to infinity at any moment but rather keeps on decreasing as it continues to experience compression even after the failure of the lower sensor along with the surrounding plies.

Cyclic tests were performed under similar conditions on identical specimens. The tests comprising of 10 cycles were conducted for a maximum displacement of 0.5 mm during each loading cycle. Force-displacement plot as well as normalized resistance response of the two sensors during loading and unloading cycles is shown in Figure 12.

Figure 12: Cyclic 3-point bending test for glass laminated composite (a) Force-displacement plot; (b) Normalized resistance curve for the two sensors against time [55].

The hysteresis in the sensor response can be attributed to the viscoelastic nature of the sensor itself and the host matrix in the laminated composite. Furthermore the unloading curves show greater noise in their response. This is conjectured to be due to the stick-slip mechanism operative at the sensor matrix interface. Another possible reason is the nature of 3-point bending fixture. The unloading phase during 3-point bending test causes the specimen to vibrate as it is loosely held between the three points. These vibrations in the specimen during unloading appear as noise in the sensor response. Another observation can be made related to the difference in the upper and lower sensor responses. The upper sensor appears to be noisier as compared to the lower sensor in terms of normalized resistance output. These differences originate from the dissimilarities in the energy absorption and release mechanisms operative under compression and tension in the top and bottom sensors respectively.

The 2D laminated composites with integrated filament sensors have shown promise for use in smart composite parts in automotive and aerospace industries. The developed sensors are capable of detecting

all the fracture events in addition to maintaining complete stress-strain history of the composite part when strategically integrated. This would not only help in carrying out in-situ on-line SHM but will also provide valuable information about the failure behavior and fracture modes in composites. The information can be used to improve design and to conceive more damage tolerant composites. Furthermore the sensors can be integrated during manufacturing of the reinforcement or during the lay-up. This would allow the integration of sensors in different types of reinforcements apart from those which are manufactured using textile technologies.

3D woven smart composites: Nauman et al. used filament sensors described earlier for insertion in a 3D orthogonal/layer-to-layer interlock reinforcement in order to manufacture 3D woven smart composite [56]. The insertion was carried out on a conventional loom (ARM PATRONIC) in the weft direction. The sensor insertion during weaving ensured that the sensor followed the same trajectory as the reinforcing filaments. In order for the sensor to detect tensile loads, the sensor was inserted in the middle of the reinforcement. The filament sensor was coated with Latex Abformmasse (VossChemie) in order to insulate it from the conductive reinforcing filaments made of carbon. The architectural parameters for the reinforcement are summarized in Table 3 [56].

Table 3: Architectural parameters for the reinforcement© [2010] IEEE. Extracted from [56]

Parameter	Units	Value
Linear density of warp tow	g/km	200
Linear density of weft tow	g/km	200
Average thickness of reinforcement	mm	6.5
Warp tow density	tows/cm	24
Weft tow density	tows/cm	169
Areal weight	g/m ²	3908
Fiber volume fraction	%	34.16

SEM cross section and tomographical depiction of the sensor embedded in composite are shown in Figure 13-a & b respectively.

Figure 13: a) Transversal section (SEM), b) Longitudinal section (tomography) of the sensor© [2010] IEEE.
Extracted from [56]

The reinforcement specimens with embedded sensors were removed from the loom and impregnated with epoxy EPOLAM 5015 using VARTM process as described earlier. The composites were allowed to cure for 24 hours and then post cured for 6 hours at 60°C in order to ensure complete crosslinking of epoxy chains. The specimens having dimensions of 25 cm X 2.5 cm were then cut from the cured sheet such that each specimen had a sensor in the center. A cross-sectional image of the composite with undulating tows is given in Figure 14.

Figure 14: Composite cross section in the weft direction© [2010] IEEE. Extracted from [56]

The specimens were loaded on Instron 8500 Tester in the direction parallel to the weft direction. These specimens were then subjected to quasi static tensile loading at a constant crosshead speed of 5 mm/min. The tests were carried out until failure of the composite specimens. Representative stress-strain-normalized resistance plot is shown in Figure 15.

Figure 15: Normalized resistance and stress plotted against strain for sensor inside composite© [2010] IEEE. Extracted from [56]

The stress vs. strain and normalized resistance vs. strain plots show mutual correspondence with three clearly discernible regions. The first region termed the 'initial stiff region' is the one where the composite resists the applied load. This region is characterized by high stiffness where the strong interfacial interaction allows transfer of loads towards the carbon fiber tows. This region is followed by 'tow straightening region' where the tows slip from their sockets as interfacial failure leads to splitting. This is followed by the so called 'second stiff region' where splitting gives way to the interaction of interlaced longitudinal and transversal tows which mutually resist the applied load owing to the interlocked multi-layer woven architecture of the reinforcement leading to final fracture after which the sudden drop in

load is observed. The highly interlaced interlocked structure rules out possibilities of delamination therefore the second stiff region is followed by the abrupt and complete fracture without any evidence of secondary energy absorption and dissipation mechanisms. The latex coating renders the embedded sensor highly stretchable as it remains intact after the failure of the composite as a result when the crosshead comes back to its initial position the sensor also regains its original resistance.

Figure 16: Normalized resistance against strain for integrated and out of composite sensors© [2010] IEEE. Extracted from [56]

A comparison of the normalized resistance response of the in-situ (embedded) and out of composite sensors is presented in Figure 16. The initial region up till ~0.20 % strain is identical for both the sensor outputs after which the sensor responses part ways which coincides with the beginning of the second stiff region. This is essentially an indication of the influence of the interface and surrounding matrix & fibers on embedded sensor as compared to the unconstrained sensor which follows a linear trajectory. The ability of the sensor to follow the trajectory when woven inside the reinforcement and follow the failure mechanism of the host composite are the abilities which make the embedded sensor especially useful for structural health monitoring in smart composites.

In order to further elaborate the damage sensing capability of this concept, two sensors were inserted in weft; one in the 2nd layer and the other one in the 12th layer in 25 layered layer-to-layer interlock structure with orthogonal bonding depth of 2 layers, on ARM PATRONIC weaving loom [57]. These two sensors were meant to follow the deformation and failure mechanisms in the top and bottom of the composite specimens during flexural tests. After weaving, the reinforcement was impregnated with the epoxy resin, cured, post cured and cut into specimens of desired dimensions (16.5 cm X 1.5 cm) as described earlier. Each of the specimens containing two sensors was subjected to 3 point bending scenario on Instron 1185 Tester. A constant crosshead speed of 3.5 mm/min was maintained and tests were performed till fracture of the specimens. Again the sensors integrated in the top and bottom were found to follow the

deformation patterns and failure mechanisms particular to 3D woven composites under flexural loading scenarios.

Macro-scale integration-Screen printed/surface deposited sensors: An alternative to cumbersome approaches discussed earlier could be the deposition of CPC solution on the surface of composite parts using various techniques such as screen printing or slot dyeing traditionally used in textile industry for printing decorative motifs and patterns. Since such sensors are applied at the surface, they are only capable of monitoring strain and detecting damage at the macro-scale.

One such approach has been explored by T.A. Khan et al [58]. They have employed screen printing for the deposition of CPC solution comprising of conductive Nano filler dispersed in thermoplastic polystyrene matrix. The glass fiber woven laminated composite specimens were prepared using standard VARTM set-up followed by curing and post curing cycles recommended for epoxy resin Araldite LY5052 and hardener Aradur 5052 provided by HUNTSMAN (USA). The laminated composite specimens were then cut into specimens of 25 cm X 2.5 cm X 1.9 mm dimensions. The specimens were then notched using diamond tipped drilling bits. Two sets of specimens were drilled with 2.5 mm and 4 mm notch size respectively. The CPC solution was then deposited on the notched specimens in rectangular pattern of 5 X 0.5 cm² using commercially available screen of 250 M mesh size. The notches of different sizes allowed observing sensor response to pre-existing damage and resulting local stress concentrations, due to spatial proximity of the deposited sensing tracks to the notches. The gauge factors calculated for the two sets of specimens with different notch sizes indicated a variation dependent on the notch size signifying sensitivity to the induced damage.

In the similar vein M. Anas et al. [44] used conductive graphene Nano platelets (GNPs) dispersed in thermoplastic polystyrene matrix to obtain strain sensors in the form of sheets as shown in Figure 17.

Figure 17: Electrical connections in GNPs-PS strain gauge using silver conductive paint and copper wires [44].

Reprinted by permission from: [Springer] [Journal of the Brazilian Society of Mechanical Sciences and Engineering] [Structural health monitoring of GFRP laminates using graphene based smart strain gauges, M. Anas, M. A. Nasir, Z. Asfar, S. Nauman, M. Akalin, and F. Ahmad], [COPYRIGHT] (2018).

These sheets were then pasted over the woven glass fiber laminated composite surface where strain monitoring was desired much like traditional metal foil resin bonded strain gauges. Three variants of these GNP based strain gauges were prepared by varying the concentration of GNPs (2%, 5% and 6%-wt. respectively). It was found that the electrical resistance gradually decreased by increasing the concentration of GNPs. The results are summarized in Figure 18 [44].

Figure 18: Comparison of initial resistances of smart (strain) gauges with and without silver paint connections at different concentrations of GNPs [44].

Reprinted by permission from: [Springer] [Journal of the Brazilian Society of Mechanical Sciences and Engineering] [Structural health monitoring of GFRP laminates using grapheme based smart strain gauges, M. Anas, M. A. Nasir, Z. Asfar, S. Nauman, M. Akalin, and F. Ahmad], [COPYRIGHT] (2018).

The woven laminated composite specimens with pasted strain gauges were tested under monotonic tensile loading. The normalized resistance output was compared with a traditional strain gauge as well. The higher concentrations of 5% and 6% by weight demonstrated higher sensitivities (gauge factors) than those of traditional metal foil strain gauges (~ 2). These gauge factors were achieved for much lower concentrations than reported earlier for CNPs owing to exceptionally high electrical conductivity of GNPs. Individual normalized resistance response for the GNP based strain gauges and their mutual comparison is presented in Figure 19 [44].

Figure 19: Change in normalized resistance plotted against strain for a) GNPs-PS smart strain gauge at 2% concentration by weight. b) GNPs-PS smart strain gauge at 5% concentration by weight. c) GNPs-PS smart strain gauge at 6% concentration by weight. d) Comparison of gauge factors for GNPs-PS smart strain gauges at three different concentrations [44].

Reprinted by permission from: [Springer] [Journal of the Brazilian Society of Mechanical Sciences and Engineering] [Structural health monitoring of GFRP laminates using graphene based smart strain gauges, M. Anas, M. A. Nasir, Z. Asfar, S. Nauman, M. Akalin, and F. Ahmad], [COPYRIGHT] (2018).

In a related work R. Jan et al. [42] reported preparation of graphene Nano sheets (GNS) through liquid phase exfoliation method. The sheets comprised of a few layers (3-4) with an aspect ratio of ~ 1272 . The liquid exfoliated graphene Nano sheets were dispersed in thermoplastic polyurethane. Uniform dispersion was achieved through ultra-sonication which rendered the thermoplastic sheet conductive. The composite sheets were molded in the form of films which were then cut in the form of 'smart sensing layers' and pasted over the laminated glass fiber woven composites. The smart composites thus achieved were subjected to both monotonic and cyclic loading. The normalized resistance response of the 'smart sensing layers' demonstrated reasonably elevated strain gauges and linearity under monotonic loading conditions whereas the cyclic response also exhibited sensor fidelity for strain monitoring albeit with some characteristic hysteresis.

The results demonstrate feasibility of using such Nano composite strain gauges for macro scale monitoring of composites by surface mounting of gauges at strategic locations according to the intended application

and expected loads in the composite part. This approach of surface application of Nano composite strain gauges can be used in lieu of printing approach described earlier where printing is not feasible.

Such gauges can be designed with exceptionally high sensitivities surpassing those of traditional metal foil strain gauges in various sizes and geometries to suit the intended application area. Innovative solutions have been proposed recently to achieve exceptional gauge factor for such sensors by manipulating the microstructure. The concept of “cracked smart film” has been introduced by Lubineau et al. [45, 59, 60] (Figure 20), and results in super sensitive ($GF > 10^7$) and highly stretchable sensors that can be mounted either on classical laminated composites or in more deformable structures such as soft robots. The key concept of these sensors is to introduce a pre-designed pattern of cracks in a functional piezoresistive film (usually a mat of CNT obtained by membrane filtration of a CNT suspension). The cracks confer super sensitivity to the film when stretched, through different mechanism (transverse cracks opening, induced super piezoresistive local delamination) [61]. This concept has been tested both for planar systems or for fibers and is very promising for wearable super sensitive human-machine interfaces [62].

Figure 20. Key features of the developed sensors: (a) laser- engraving process for generating partial cracks on the SWCNT paper, (b) typical, high crack density SWCNT paper in PDMS when stretched from 0 to 150% strain, (c) Resistance changes under incremental cyclic stretching/relaxing of a high crack density sensor. The maximum stretchability of the sensor is 153%.

[45] - Reproduced by permission of The Royal Society of Chemistry.

Conclusion: Textile composites are inherently hierarchical in nature with hierarchies spanning from micro (fibers and filaments) to meso (tows) and macro-scale (lamina and laminate). The integration of Nano composites with textile composites can therefore be carried out at different levels of hierarchy. An approach has been presented which helps classifying these composites on the basis of scale at which the integration (Nano- & Textile-) has been carried out. Taking advantage of the exceptional conductivities of carbonaceous Nano fillers, the integration at different hierarchical levels results not only in smart threads, 2D and 3D reinforcements but various sensing techniques which can be employed at macro scale such as screen printing of Nano composite solution for printing of sensing tracks on composite laminates.

Depending on the scale of integration, various different integration techniques, ranging from extru-coating (micro-scale) to weaving (meso-scale) and screen printing and slot dyeing (macro-scale) can be employed with their peculiar advantages and disadvantages, attesting to the polyvalence of textile technologies.

References:

1. Davidson, R., *Smart composites: where are they going?* Materials & Design, 1992. **13**(2): p. 87-91.
2. Staszewski, W., S. Mahzan, and R. Traynor, *Health monitoring of aerospace composite structures—Active and passive approach*. composites Science and Technology, 2009. **69**(11-12): p. 1678-1685.
3. Medeiros, R.d., *Development of a criterion for predicting residual strength of composite structures damaged by impact loading*. 2016, Universidade de São Paulo.
4. Almuhammadi, K., T.K. Bera, and G. Lubineau, *Electrical impedance spectroscopy for measuring the impedance response of carbon-fiber-reinforced polymer composite laminates*. Composite Structures, 2017. **168**: p. 510-521.
5. Greenhalgh, E., *Delamination-dominated failures in polymer composites*. Failure Analysis and Fractography of Polymer Composites. Woodhead Publishing Lmted., Oxford, 2009: p. 164-237.
6. Long, A.C., *Design and manufacture of textile composites*. 2005: Elsevier.
7. Boussu, F., I. Cristian, and S. Nauman, *General definition of 3D warp interlock fabric architecture*. Composites Part B: Engineering, 2015. **81**: p. 171-188.
8. Nauman, S. and I. Cristian, *Geometrical modelling of orthogonal/layer-to-layer woven interlock carbon reinforcement*. The Journal of The Textile Institute, 2015. **106**(7): p. 725-735.
9. Nauman, S., I. Cristian, and F. Boussu, *Geometrical modelling of angle warp interlock fabrics*. Journal of the Textile Institute, 2012. **103**(7): p. 766-776.
10. Saleh, M.N., et al., *The effect of z-binding yarns on the electrical properties of 3D woven composites*. Composite Structures, 2017. **182**: p. 606-616.
11. Saleh, M.N., et al., *Investigating the potential of using off-Axis 3D woven composites in composite joints' applications*. Applied Composite Materials, 2017. **24**(2): p. 377-396.
12. Paul, D.R. and L.M. Robeson, *Polymer nanotechnology: nanocomposites*. Polymer, 2008. **49**(15): p. 3187-3204.
13. Janakiram, S., et al., *Performance of nanocomposite membranes containing 0D to 2D nanofillers for CO2 separation: A review*. Membranes, 2018. **8**(2): p. 24.
14. Han, Z. and A. Fina, *Thermal conductivity of carbon nanotubes and their polymer nanocomposites: A review*. Progress in polymer science, 2011. **36**(7): p. 914-944.
15. Ma, P.-C., et al., *Enhanced electrical conductivity of nanocomposites containing hybrid fillers of carbon nanotubes and carbon black*. ACS applied materials & interfaces, 2009. **1**(5): p. 1090-1096.
16. Grigoriadou, I., et al., *Effect of different nanoparticles on HDPE UV stability*. Polymer degradation and stability, 2011. **96**(1): p. 151-163.
17. Strong, A.B., *Fundamentals of composites manufacturing: materials, methods and applications*. 2008: Society of Manufacturing Engineers.
18. Rafiee, M.A., et al., *Enhanced mechanical properties of nanocomposites at low graphene content*. ACS nano, 2009. **3**(12): p. 3884-3890.
19. Tjong, S.C., *Structural and mechanical properties of polymer nanocomposites*. Materials Science and Engineering: R: Reports, 2006. **53**(3-4): p. 73-197.

20. Lubineau, G. and A. Rahaman, *A review of strategies for improving the degradation properties of laminated continuous-fiber/epoxy composites with carbon-based nanoreinforcements*. Carbon, 2012. **50**(7): p. 2377-2395.
21. Lau, K.-t., M. Lu, and K. Liao, *Improved mechanical properties of coiled carbon nanotubes reinforced epoxy nanocomposites*. Composites Part A: applied science and manufacturing, 2006. **37**(10): p. 1837-1840.
22. Choi, S.-M. and H. Awaji, *Nanocomposites—a new material design concept*. Science and Technology of Advanced Materials, 2005. **6**(1): p. 2-10.
23. Siddiqui, N.A., et al., *Tensile strength of glass fibres with carbon nanotube–epoxy nanocomposite coating*. Composites Part A: applied science and manufacturing, 2009. **40**(10): p. 1606-1614.
24. Vlasveld, D.P., et al., *Continuous fibre composites with a nanocomposite matrix: Improvement of flexural and compressive strength at elevated temperatures*. Composites Part A: applied science and manufacturing, 2007. **38**(3): p. 730-738.
25. Zahid, S., et al., *Experimental analysis of ILSS of glass fibre reinforced thermoplastic and thermoset textile composites enhanced with multiwalled carbon nanotubes*. Journal of Mechanical Science and Technology, 2019. **33**(1): p. 197-204.
26. Anas, S., et al. *Influence of MWCNTs as secondary reinforcement material in glass fiber/epoxy composites fabricated using VARTM*. in *International Conference on Solid State Physics; ICSSP: Pakistan*. 2013.
27. Fiedler, B., et al., *Fundamental aspects of nano-reinforced composites*. composites Science and Technology, 2006. **66**(16): p. 3115-3125.
28. Srikanth, I., et al., *Effect of amino functionalized MWCNT on the crosslink density, fracture toughness of epoxy and mechanical properties of carbon–epoxy composites*. Composites Part A: applied science and manufacturing, 2012. **43**(11): p. 2083-2086.
29. Ye, Y., et al., *High impact strength epoxy nanocomposites with natural nanotubes*. Polymer, 2007. **48**(21): p. 6426-6433.
30. Ahmad, K. and W. Pan, *Hybrid nanocomposites: a new route towards tougher alumina ceramics*. composites Science and Technology, 2008. **68**(6): p. 1321-1327.
31. Yu, A., et al., *Nanostructured electrochemical sensor based on dense gold nanoparticle films*. Nano letters, 2003. **3**(9): p. 1203-1207.
32. Pandey, S., G.K. Goswami, and K.K. Nanda, *Green synthesis of biopolymer–silver nanoparticle nanocomposite: An optical sensor for ammonia detection*. International journal of biological macromolecules, 2012. **51**(4): p. 583-589.
33. Valenkov, A., et al., *Polymeric composite systems modified with allotropic forms of carbon*. Russian Journal of Applied Chemistry, 2011. **84**(5): p. 735-750.
34. Rahman, I.A. and V. Padavettan, *Synthesis of silica nanoparticles by sol-gel: size-dependent properties, surface modification, and applications in silica-polymer nanocomposites—a review*. Journal of Nanomaterials, 2012. **2012**: p. 8.
35. Mora, A., F. Han, and G. Lubineau, *Computational modeling of electrically conductive networks formed by graphene nanoplatelet–carbon nanotube hybrid particles*. Modelling and Simulation in Materials Science and Engineering, 2018. **26**(3): p. 035010.
36. Segev-Bar, M. and H. Haick, *Flexible sensors based on nanoparticles*. ACS nano, 2013. **7**(10): p. 8366-8378.
37. Kowalczyk, K., S. Kugler, and T. Spychaj, *Antistatic polyurethane coats with hybrid carbon nanofillers*. Polimery, 2014. **59**(9): p. 650–655.
38. Cochrane, C., et al., *Design and development of a flexible strain sensor for textile structures based on a conductive polymer composite*. Sensors, 2007. **7**(4): p. 473-492.

39. Nauman, S., *Geometrical modelling and characterization of 3D warp interlock composites and their on-line structural health monitoring using flexible textile sensors*. 2011, Lille 1.
40. Nasir, M.A., et al., *Smart sensing layer for the detection of damage due to defects in a laminated composite structure*. Journal of Intelligent Material Systems and Structures, 2015. **26**(17): p. 2362-2368.
41. Cristian, I., et al., *Electro-conductive sensors and heating elements based on conductive polymer composites in woven structures*, in *Advances in modern woven fabrics technology*. 2011, IntechOpen.
42. Jan, R., et al., *Liquid exfoliated graphene smart layer for structural health monitoring of composites*. Journal of Intelligent Material Systems and Structures, 2017. **28**(12): p. 1565-1574.
43. Nauman, S., et al., *Piezoresistive Fibrous Sensor for On-Line Structural Health Monitoring of Composites*. Smart Sensors for Industrial Applications, 2016: p. 455.
44. Anas, M., et al., *Structural health monitoring of GFRP laminates using graphene-based smart strain gauges*. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2018. **40**(8): p. 397.
45. Xin, Y., et al., *Laser-engraved carbon nanotube paper for instilling high sensitivity, high stretchability, and high linearity in strain sensors*. Nanoscale, 2017. **9**(30): p. 10897-10905.
46. Zhou, J. and G. Lubineau, *Improving electrical conductivity in polycarbonate nanocomposites using highly conductive PEDOT/PSS coated MWCNTs*. ACS applied materials & interfaces, 2013. **5**(13): p. 6189-6200.
47. Gao, L., et al., *Sensing of damage mechanisms in fiber-reinforced composites under cyclic loading using carbon nanotubes*. Advanced functional materials, 2009. **19**(1): p. 123-130.
48. Chen, Q., et al., *3D printing biocompatible polyurethane/poly (lactic acid)/graphene oxide nanocomposites: anisotropic properties*. ACS applied materials & interfaces, 2017. **9**(4): p. 4015-4023.
49. Jain, S.K., *Fabrication of Polylactide Nanocomposite Filament Using Melt Extrusion and Filament Characterization for 3D Printing*. 2017.
50. Gao, S.I., et al., *Glass fibers with carbon nanotube networks as multifunctional sensors*. Advanced functional materials, 2010. **20**(12): p. 1885-1893.
51. Tai, Y. and G. Lubineau, *Double-Twisted Conductive Smart Threads Comprising a Homogeneously and a Gradient-Coated Thread for Multidimensional Flexible Pressure-Sensing Devices*. Advanced Functional Materials, 2016. **26**(23): p. 4078-4084.
52. Zhang, Y., et al., *All-printed strain sensors: Building blocks of the aircraft structural health monitoring system*. Sensors and Actuators A: Physical, 2017. **253**: p. 165-172.
53. Lomov, S.V., et al., *Textile composites: modelling strategies*. Composites Part A: applied science and manufacturing, 2001. **32**(10): p. 1379-1394.
54. Asfar, Z., et al., *Development of flexible cotton-polystyrene sensor for application as strain gauge*. IEEE Sensors Journal, 2016. **16**(24): p. 8944-8952.
55. Nauman, S., I. Cristian, and V. Koncar, *Simultaneous Application of Fibrous Piezoresistive Sensors for Compression and Traction Detection in Glass Laminate Composites*. Sensors, 2011. **11**(10): p. 9478-9498.
56. Nauman, S., et al., *Online measurement of structural deformations in composites*. IEEE Sensors Journal, 2010. **11**(6): p. 1329-1336.
57. Nauman, S., I. Cristian, and V. Koncar, *Intelligent carbon fibre composite based on 3D-interlock woven reinforcement*. Textile Research Journal, 2012. **82**(9): p. 931-944.
58. Khan, T.A., et al., *Screen-printed nanocomposite sensors for online in situ structural health monitoring*. Journal of Thermoplastic Composite Materials, 2018: p. 0892705718805131.

59. Zhou, J., et al., *Ultrasensitive, Stretchable Strain Sensors Based on Fragmented Carbon Nanotube Papers*. ACS Applied Materials & Interfaces, 2017. **9**(5): p. 4835-4842.
60. Xin, Y., et al., *Making a Bilateral Compression/Tension Sensor by Pre-Stretching Open-Crack Networks in Carbon Nanotube Papers*. ACS Applied Materials & Interfaces, 2018. **10**(39): p. 33507-33515.
61. Nasr Saleh, M. and G. Lubineau, *Understanding the mechanisms that change the conductivity of damaged ITO-coated polymeric films: A micro-mechanical investigation*. Solar Energy Materials and Solar Cells, 2014. **130**: p. 199-207.
62. Zhou, J., et al., *Deformable and wearable carbon nanotube microwire-based sensors for ultrasensitive monitoring of strain, pressure and torsion*. Nanoscale, 2017. **9**(2): p. 604-612.