The introduction of fiber-reinforced plastics (FRPs) in industries such as aerospace, marine, and automotive, has resulted in a necessity to monitor the structural integrity of composite structures and materials. Apart from development of traditional non-destructive testing methods which are performed off-line, there is a growing need to integrate structural health monitoring (SHM) systems within composite structures. An interesting route toward multifunctional composite materials with integrated SHM capabilities is through the introduction of carbon nanotubes (CNTs) in fiber-reinforced composites as this provides not only integrated damage sensing capability, but may, at the same time, also lead to some additional mechanical reinforcement. Since the first use of CNTs for damage sensing in composite laminates, a significant number of studies have dealt with this topic, but a systematic understanding on the use of CNTs in FRPs for SHM is still lacking. Furthermore, a significant gap remains between results obtained in the laboratory and industrial applications. This review reports on the progress of this topic so far. The reviewed work had been categorized from model studies on single fiber composites to laminated composites under different loading conditions, as well as the development of reliable damage-sensing systems which could be transferred to real applications.

**Keywords** Carbon nanotubes, Damage sensing, Structural health monitoring, Fiber-reinforced plastics, Hierarchical composites, Nanoengineered composites

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aircraft (Fig. 1). In this review, different concepts are introduced and briefly analyzed, with a special focus on the use of carbon nanotubes (CNTs) as integrated sensors for health monitoring in FRPs.

Various NDT methods have been applied in this field to examine and evaluate internal damage in composites. Acoustic emission (AE) is one of the most commonly used NDT methods for damage inspection and quality control. When an internal damage occurs, the released stress generates an elastic wave which can be recorded by a piezoelectric sensor on the specimen surface. By analyzing the collected information, the location as well as the possible failure modes can be identified.4–7

Another commonly used NDT technology is ultrasonics which uses low-frequency acoustic pulses to detect the internal continuity of composite structures. Computed tomography has also been used more widely nowadays for inspection due to its accuracy in evaluating data, especially for complex engine components. Unfortunately, most of those NDT tests not only require special equipment to perform the damage detection, but also strongly depend on the experience of engineers to interpret data as well as involve additional assembly time, costs, and difficulties of monitoring the health of FRPs continuously. The downtime nature of these NDT methods, which often require that examinations are performed during out-of-service periods, increases the lifetime costs even further.

Hence, embedded sensors such as fiber optics or smart piezoelectric films or coatings have been introduced into FRPs to detect internal deformation and damage in-service. For instance, coated piezoelectric sensors either with or without CNTs,8–14 could be used to detect the deformation of the coated region through a change of electrical signals. This method provides the possibility to monitor the structural health during service life, avoiding complex downtime inspection and components assembly. However, it is worth noting that there is no structural contribution from most of those embedded sensors, and in certain cases, they may even lower the mechanical performance of components.15 For example, the introduction of optical fibers in composite laminates may lead to early matrix cracking as the additional interfaces generated by these embedded sensors may weaken the composite in use, limiting their application in real structural components.

Self-sensing concepts which utilize electrical methods to detect the internal health status of composites have been introduced into this field for carbon fiber-reinforced plastics (CFRP) using the intrinsically conductive carbon fibers (CFs) as damage sensors. The advantage of self-sensing methods is that all original mechanical properties are preserved while internal damage can be sensed and monitored.16–22 By using the structural component itself as a sensor to detect damage, this concept overcomes issues related to the reduction of mechanical performance and durability as a result of the introduction of sensors in laminated composites. In contrast to electrically conductive CFRPs, insulating glass fiber-reinforced plastics (GFRPs) cannot be used for electrical damage sensing concepts, while various GFRPs applications like wind turbine blades still require advanced in-service damage detection systems. Apart from the highly anisotropic conductivities of CFs, the failure modes that can be self-sensed in CFRPs are mostly fiber breakage which normally occurs near the end of a component service life rather than early stage damage like
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Matrix cracking or delaminations. Failure modes like matrix cracking or delaminations are harder to sense using electrical methods as the surrounding polymer matrix is typically insulating. In order to be able to apply the electrical sensing concept to insulating GFRPs, and to detect early matrix-dominated failure modes in CFRPs, the polymer matrix needs to become electrically conductive. This can be achieved either through the introduction of conductive nanofillers in the polymer matrix or surface functionalization of reinforcing fibers with conductive nanofillers. Early studies on the use of CNTs as molecular sensors around the year 2000 guided the potential routes toward multifunctional composites, while detailed reviews on CNT-based sensors and actuators were already published by Chou et al. around 2008.25,26 An attempt to compare the strengths and limitations of several SHM/NDT methods is presented in Fig. 2 on the basis of convenience, integrity, and potential to detect different failure modes in FRPs, where integrity refers to the necessity to use less additional equipment and less interference with original material properties; and convenience refers to a realistic potential for in situ applications and dimensional limitations. Color index from top to bottom stands for the possibility to detect multiple failure modes ranging from high to low.

Figure 2 Comparisons between various SHM/NDT methods and their possibility of in situ damage detection in composites

CNTs were first introduced into FRPs as sensors for SHM purposes by Fiedler et al. in 2004.27 Since then, several studies exploring the use of CNTs for damage sensing in FRPs have been conducted, particularly in the last 5 years (Fig. 3). Because of their extraordinary mechanical and electrical properties, CNTs have become the nanofiller of choice for many multifunctional applications over the last decade.28–34 With respect to electrical properties their high aspect ratio guarantees a very low percolation threshold which does not significantly compromise the original resin properties. By introducing CNTs into insulating polymer matrices, various matrix-dominated failure modes can be sensed and detected, providing a promising route for next-generation SHM systems. The use of CNTs in FRPs also provides the possibility of in-service health monitoring, without complicated equipment and intensive labor requirements. In-service damage detection can greatly save aircraft or wind turbine downtime, in other words, providing more in-service time, improving efficiency and reducing costs.

Although a good amount of research has been conducted in this field, a systematic understanding of the use of CNTs in FRPs for damage sensing and health monitoring purposes is lacking, not to mention the gap that still exists between laboratory successes and real industrial applications in structural components. In the present paper, the use of CNTs for damage sensing in composites is reviewed, with the aim to contribute to a better understanding and systematic comparison of the field. Apart from this, special efforts have been made to analyze the existing knowledge from an end-user point of view, to classify various works and data, and list requirements from industry (i.e. SHM in aircraft), trying to reduce the gap between laboratory data and real applications.

Model studies on single fiber composites

Single fiber composites are often chosen as model systems to study interfacial properties of composites and for this reason, they have also been used to study the effect of CNT sensory networks within interfacial regions. Various research works have been conducted to understand how conductive interfacial networks behave during loading which is an important aspect of damage sensing in FRPs, especially for loading situations where interfacial debonding is likely to occur.

Park et al.35,36 have combined an electrical sensing method together with traditional AE, in order to obtain damage sensing results. In this study, CNTs were dispersed in epoxy using a solvent and after solvent evaporation, composites with CF positioned at the mid-plane were manufactured, as illustrated in Fig. 4.36 During tensile loading along the fiber direction, fiber breakage occurred and electrical sensing signals as well as AE signals were collected. For the specimen with extremely...
These model studies showed some promise of the use of CNTs into FRPs. Even in combination with conductive CF, CNTs showed their potential for damage sensing, not to mention their potential benefits through additional multi-scale mechanical reinforcement. After the establishment of a percolating network, larger amounts of CNTs reduce the sensitivity of the electrical damage sensing signal, which was also confirmed by other sensing studies based on CNT networks. Apart from the concentration, the solvent used to facilitate CNT dispersion at the manufacturing stage also affected the sensing results. Poor solvents such as water gave a lower electrical resistivity change than acetone and 2-propanol as they lead to poor dispersion and poor sensory networks. Therefore, both CNT loading and dispersion state are key factors that need to be addressed for optimized damage sensing behavior.

With the aim of highlighting the potential of percolated CNT networks as sensory systems, insulating glass fiber (GF) was also used in similar model composite studies. These model studies showed promise in terms of incorporating CNTs into FRPs. Even in combination with conductive CF, CNTs demonstrated their potential for damage sensing, along with additional multi-scale mechanical reinforcement. After the formation of a percolating network, larger amounts of CNTs can reduce the sensitivity of the electrical damage sensing signal, which was also confirmed in other studies using CNT networks. Apart from concentration, the solvent used during the manufacturing process significantly influenced the sensing outcomes. Poor solvents such as water resulted in lower electrical resistivity changes compared to acetone and 2-propanol, which caused poor dispersion and sensory networks. Therefore, both CNT loading and dispersion state are critical factors to consider for optimizing damage sensing behavior.

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to a reduction in single fiber tensile strength. These studies showed that in order to be successful in SHM applications, stable and repeatable sensing signals, as well as no degradation of original material properties are key factors.

Based on these results, Gao et al. improved the dip-coating technique for CNTs using a surfactant and controlled pH, generating a multifunctional interface to sense various stimuli. Single GFs with deposited CNTs at the surface were characterized for electrical properties, piezoresistivity, humidity, and temperature sensitivity (Fig. 6). Although the strength and other mechanical performances of these CNT-modified GF interfaces were not measured in this research work, and the use of surfactant, pH control, as well as the complicated manufacturing might limit scale-up, these model studies did unveil the possibility of using CNTs directly onto insulating fibers such as GFs to produce multifunctional composites.

Apart from depositing CNTs directly onto carbon or glass fiber surfaces for sensing functionalities, polymer/CNT sizings and coatings have also been studied as interface sensors. Rausch and Mäder introduced an alternative route to incorporate CNTs into FRPs at the fiber/matrix interface by sizing or coating a CNT/polymer film former onto GF. For their CNT/GF/PP model composites, 0.5 wt.% CNT/PP film was coated onto GF surfaces, followed by annealing process to achieve a more homogeneous coating (Fig. 7). The CNT/polymer coating enabled the localization of the sensory network within the interfacial region rather than being distributed throughout the matrix. However, for such a coating

![Figure 5](image_url)  
**Figure 5** In situ damage sensing on single glass fiber with CNT coating via EPD. Different stages of fiber under tensile loading are shown in the graph together with the corresponding electrical sensing signals. Source: Reprint with permission from Ref. 42

![Figure 6](image_url)  
**Figure 6** Single glass fiber with CNT coating as sensor for various stimuli: a sensing signals under static tensile stress until failure; b under cyclic tensile loading; c sensing signals with relative humidity changes; d signal changes with temperature. Source: Reprint with permission from Ref. 13
to be effective, it needs to be continuous and homogeneous (>10 wt.%). During tensile loading, interface failure as well as GF breakage could be identified (Fig. 8). The sensitivity of such a multifunctional coating could be adjusted by changing the coating thickness and CNT content in the coating. Both thicker coatings and higher CNT loadings in the coating led to a reduction in sensitivity of the coating. Similar effects were also found in other studies.35–39,41

Although problems like strength reduction of the original microfiber as well as issues related to complex additional processing steps exist, these single fiber model studies have shown great potential of the use of CNT networks as sensors for the detection of interfacial damage in both conductive and insulating reinforcing fibers. Localized CNT sensory networks on insulating GFs can introduce multifunctionality in their composites, regardless of polymer or interface.

**Model studies on laminates**

After the initial idea of using CNTs as multifunctional sensors for FRPs,23,24,27 numerous studies based on GF/CNT (or CF/CNT) hybrid multi-scale composites have been conducted34–40 to further explore the potential of CNT damage sensing methodologies in laminated composites. It is well established that damage in composite laminates starts from matrix-dominated failure modes such as matrix cracking and delamination, followed by fiber breakage which normally occurs near the end of the composites’ lifetime. The introduction of CNT networks within an insulating matrix acts like a neuron sensory networks for FRPs, enabling the detection of microcrack initiation and propagation, with the possibility of identifying the damage stage under certain conditions. Both static and cyclic loading conditions have been studied and are reported below, while also different manufacturing processes such as calendering or solution-based processes as well as specific specimen preparation methods are briefly described for each work.

**Static loadings**

Thostenson and Chou46 used high shear mixing methods (calendering and three-roll mill) to disperse MWCNTs in epoxy resin, creating a percolating network for the onset of damage detection and evolution in GFRPs. During their specifically designed mechanical tests, interlaminar delamination and transverse microcracking was evaluated in unidirectional and cross-ply laminates, respectively. In the delamination tests (Fig. 9a), the electrical resistance increased significantly when delamination started and then progressively increased until the specimen failed. On the other hand, in the case of microcracking detection (Fig. 9b), the electrical resistance increased stepwise after crack initiation. These differences in sensing signal response opened up the possibility to identify different failure modes by using conductive CNT networks. The authors also compared the initial undamaged and damaged electrical resistance, and showed that it provided a more sensitive route to evaluate self-healing efficiency compared to traditional stiffness measurement since the stiffness of
with and without sizing agent. By using a sizing agent, the dispersion of CNTs in epoxy resin became non-uniform which lead to a reduction in mechanical performance compared to uniformly dispersed specimen via three-roll milling. During tensile testing, the resistance change per unit length was also found to be much less for non-uniformly dispersed specimen. This was not only due to agglomeration of sized CNTs, but also the results of higher CNT concentrations in these specimens.

Gao et al.’s research showed the effect of CNT dispersion and concentration on sensing properties. In the case of CNTs, a uniform dispersion is preferred to create conductive pathways for electrons during loading. However, it is worth mentioning that for structural applications where the critical failure mode or damage prone region is often known, the localization of CNTs within these regions can be much more effective and efficient. In the case of CFRPs based on conductive CFs, research results showed that the presence of CNTs within the polymer matrix not only improved the electrical conductivity in transverse and through-thickness direction of composite laminates, but also enhanced the sensitivity to damage through more obvious resistance changes. This can be attributed to the more sensitive neuron-like CNT percolated network in between CFs, as explained elsewhere.

Cyclic loadings
Apart from static testing conditions, cyclic loading was performed with the aim of evaluating damage progression as well as identifying the failure stages during the composites’ usage. Thostenson and Chou examined microstructural damage evolution under cyclic loading with CNTs dispersed in epoxy via a calendering method. Cracks initiated within the 90° plies (Fig. 11) with the applied load increasing until crack saturation in these plies, and with CNT pullout being observed at the crack surface. For cyclic sensing (Fig. 12), the strains of...
loading cycle, while electrical sensing shows a more continuous increase throughout the test.

The possibility of using CNT networks to identify different damage stages was successfully shown in composite laminates. However, transferring these results to real composite applications remains a great challenge. For example, issues of how to adapt the differences in specimen sizes and lay-ups from model studies to real components and the ability to correlate sensing signals to failure modes remain a challenge.

However, initial results have indicated that CNT networks that establish themselves as a nerve-like sensory network within composite laminates are able to sense deformation and damage initiation and propagation, potentially providing a useful tool for health monitoring of composite structures. Moreover, initial work suggests that by analyzing the data, different failure modes and damage stages can potentially be identified.

**Damage sensing in standardized tests**

In the previous sections, it was shown that the use of CNTs in FRPs, especially in the case of insulating fibers like GF, can lead to hierarchical composites with damage sensing capability. Various stages of failure initiation and propagation, under both static and dynamic loadings, have been identified and analyzed. However, in order to replace (or combine with) existing embedded sensor SHM technologies in FRPs, improved sensitivity and reliability of signals remains a challenge. Most
characterization of sensing in standardized test conditions, the electrical sensing method could be adapted to different applications with specific failure tendencies.

Impact

Impact damage is one of the major concerns in health monitoring of FRPs. Normally, the electrical sensing signals are correlated to the impact energy during data analysis. Yesil et al. compared different treated CNTs for dispersion as well as impact damage sensing properties. Better dispersion gave better electrical sensing signals which correlated to the impact energy applied. Similar findings were reported in other research works. In another research by Arronche et al., two-probe and four-probe measurements were compared for sensing impact damage, with the four-probe method showing better reliability as it eliminates contact resistance effects.

It is worth mentioning that the impact studies listed below were not performed under ASTM D7136 for drop-weight
specimen after impact, which again was due to breakdown of internal CNT networks.

In order to apply the electrical sensing method to larger plates, Naghashpour et al.69 performed electrical grid mapping to detect internal damage in large composite laminates. Both high-velocity and low-velocity impact was applied to initiate damage, and real-time detection was achieved.

Some other CNT-related impact damage sensing studies including electrical impedance tomography,70 or sensing skins,71 etc. are not discussed here, as these works are not the main topic for this review paper.

**Fatigue**

It is well known that the fatigue life of composites is strongly affected by matrix-dominated properties.50,72,73 In fatigue, residual strain is often used as an indicator for the internal health of a composite laminate. Hence, by comparing the resistance change and number of cycles together with residual strain, the internal health condition of laminates can be revealed by electrical signals.

Yesil et al.65 followed ASTM D3039 to produce tensile specimen for fatigue testing, with various treated CNTs being introduced in the GFRP laminates. Among their results, the largest sensing signals were obtained for treated CNTs which gave better dispersion and interaction within the matrix (Fig. 15). Generally, it was found that electrical resistance increased

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**Figure 12** Damage initiation and evolution study under incremental cyclic loading in 90° mid-ply of cross-ply laminated composites: a resistance response under cyclic loading; b focused view of resistance response of fifth cycle; c substantial hysteresis response from resistance–strain curve; and d elastic modulus and resistance changes with maximum cyclic strain

Source: Reprint with permission from Ref. 63

**Figure 13** Comparison between electrical sensing and AE under incremental cyclic loading conditions, showing good correlation between electrical signals and AE counts

Source: Reprint with permission from Ref. 61
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Zhang et al. applied various routes to deliver CNTs into FRPs through interleaves for damage sensing purposes, including direct spraying deposition\(^6\) for both insulating GF and conductive CF preforms. With this simple but versatile spray coating technique, an extremely low CNT concentration (~0.01 wt.\%) could be introduced to create a percolating network for internal health monitoring under Mode-I test conditions. Fine CNT networks positioned on the surface of GFs as well as in between fibers were observed. Internal crack propagation was correlated to measured electrical signal changes, and a good correlation was reported (Fig. 19).

Zhang et al. extended this method to CF prepregs, and obtained good sensing signals.\(^6\) Compared to the CF reference laminate, the introduction of CNTs within the interfacial regions successfully improved the stability of the sensing signals. This reduction in scatter in sensing signals, which is essential for industrial applications, was attributed to changes in sensing mechanism going from physical contacts between conductive CFs to a tunneling mechanism between CNTs in percolated networks in resin-rich regions with improved stability and consistency, as illustrated in Fig. 20.

Overview of CNT damage sensing and other on-line SHM methods

The current review has demonstrated the potential of CNT networks for damage sensing from model studies to standardized composite coupon tests. Table 1 lists the majority of research studies related to damage sensing in fiber composites using CNTs. The materials used, manufacturing processes applied, as well as main results are reported. The table also indicates whether the damage sensing studies were performed using standardized ASTM/ISO tests.

For on-line SHM, in general, two main approaches are followed to integrate sensors into composites: (i) with decreasing stiffness during fatigue testing as a result of internal damage accumulation process. The existence of CNTs has also shown increased high cycle fatigue life compared to the reference.\(^5\)

Flexural loading and short beam shear loading

Thostenson and Chou\(^4\) used two different spans to promote different failure modes in three-point bending tests (Fig. 16). For short beam shear conditions, i.e. a short span-to-depth ratio of 4, electrical signals increased by several orders close to the point of shear failure, indicating rather abrupt delamination. Subsequent reloading did establish some new electrical contacts but still resulted in a much greater resistance than its initial value. For a longer span-to-depth ratio of 8, i.e. more toward pure bending conditions, a more incremental resistance change was observed, which corresponds to matrix cracking and damage accumulation.

Boger et al.\(^5\) followed ASTM D2344 for short beam shear testing of GF/CNT hybrid composites. During this interlaminar shear strength test, in-plane electrical resistance remained more or less constant until a sudden increase due to composite failure. In this study, through-thickness resistivity showed no obvious change during loading (Fig. 17). In contrast, Zhang et al.\(^7\) found that monitoring through-thickness resistance was the most effective way to detect interlaminar shear failure, as the sensing signals simultaneously changed with increasing load, providing a tool to detect early stage matrix damage. Moreover, the sensitivity of the measured electrical signals was also higher for their through-thickness measurements compared to in-plane measurement (Fig. 18).\(^7\)

Delamination

Delamination is one of the most common failure modes in composites as out-of-plane properties remain one of their weaknesses due to their laminated nature. Various studies have been conducted with the aim of improving delamination resistance through the addition of CNTs, while at the same time introducing multifunctionalities for in situ health monitoring.\(^6,7,9-7\)

Figure 14 In situ impact damage sensing using percolated CNT networks in composite laminates: in comparison with AE results (left) and damage areas measured by ultrasonic C-scan (right)

Source: Reprint with permission from Ref. 47
For industrial applications, especially for civil aircrafts where safety is always paramount, surface-mounted sensors are often favored in the short term due to their simplicity and ease of installation. These include piezoelectric sensors, eddy current sensors, and comparative vacuum monitoring (CVM). In contrast, embedded sensors like fiber Bragg grating sensors or CNTs are considered for more long-term applications due to their potential for higher sensitivity and the ability to monitor in a passive mode.

Figure 15  Resistance change under axial fatigue vs. number of cycles (top), and average residual strain vs. number of cycles under axial fatigue (bottom)
Source: Reprint with permission from Ref. 65

Figure 16  In situ damage sensing results at different span-to-depth ratios of 4 a and 8 b, together with their optical microscope images c and d, respectively
Source: Reprint with permission from Ref. 49
The study of damage sensing using CNTs (or other nanocarbons) as integrated sensing materials into FRPs is still at an early stage but has already shown great promise of both the fundamental understanding of sensing mechanisms, as well as the potential to apply this technology in composite structures. More importantly, the preservation of the original material properties. From an application point of view, novel hybrid CFRP-CNT composites are regarded as a new material system which needs to go through a long validation program before it can be certified for use in aircraft. Sensors that are attached to the outer surface without affecting the components' integrity are easier to be approved for use in current aircraft. However, surface-mounted sensors have their limitations as they have to face limited space for sensor attachments and strict operating environments, not to mention the additional equipment involved which adds more weight to the aircraft. Moreover, such sensors have difficulties to detect internal damage in composite laminates. Despite these disadvantages, nanocarbon based surface coatings are expected to be among the first CNT based sensing systems for composite structures, because of advantages over piezoelectric sensors such as lightweight and added multifunctionality through increased electrical conductivity for improved lightning strike protection (LSP).

On the other hand, regardless of the certification process, embedded sensing systems like CNT-based damage sensing technologies can be integrated into the composite components without requiring additional space or equipment, greatly saving space and weight of the complete system. In the long term, a self-sensing composite system with reliable SHM functionalities is definitely the ultimate goal for the aviation industry. Hence, for the medium- to long-term on-line SHM, the embedded or integrated sensory networks in composite materials rather than surface-mounted sensors are favored. However in order to be successful, a couple of important aspects need to be addressed from a materials point of view:

- The integrated sensor system cannot affect components' integrity and structural properties.
- The system needs to be integrated or as compact as possible, with minimum number of components involved.
- The system needs to have clear and reliable sensing signals to identify different failure modes, and good sensitivity to determine the level of damage.

Clearly, compared to other on-line SHM methods, the here presented CNT sensing technologies have advantages of integration and lightweight, preserved (or even improved) mechanical and electrical performance, potential to detect different matrix-dominated failures, as well as long-term durability for on-line damage monitoring. However, at its current stage, the technology has also some limitations and challenges, such as (i) how to position electrical circuits to build detection networks, (ii) how to decouple sensing signals from the CNT network from signals originating from the naturally conductive CFs, and (iii) how to deal with the increase in viscosity and inhomogeneous dispersion of CNTs in polymer resins and in laminate manufacturing. For the first two issues, previous SHM know-how based on existing methods could provide guidance of how to establish successful sensory networks, while combinations with other NDT or SHM methods might be required to improve its sensitivity to different failure modes. Regarding manufacturing issues, innovative methods of CNT deposition like spray coating, electrophoresis deposition, or catalytic growth of CNTs onto fiber preforms provide interesting solutions to localize the CNT networks at desired positions without affecting resin viscosity or creating filtration problems arising from flow of a CNT-filled resin through the fiber preform.

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components for on-line health monitoring. However, before this technology reaches maturity, it probably needs to be used in combination with other traditional SHM or NDT methods to deliver reliable results. For instance, in order to utilize the CNT sensing method to detect various failure modes under both static and cyclic loading conditions, a combination with AE may be needed to determine those failure modes, while it can also help to decouple the effects from the conductive CFs. However, in the long term, the use of CNTs in FRPs possesses huge potential for creating integrated self-sensing materials and structures.

Conclusions and perspectives

Fiber-reinforced composites have been used extensively to replace traditional materials like metals in many fields. To improve the reliability of these materials, integrated on-line health monitoring systems have been the topic of numerous studies for many years. In the last decade, the use of CNTs to create sensory networks that are able to detect various stages of internal damage and failure modes in composite materials has been extensively studied. Percolated networks of electrically conductive CNTs allow electrons to pass through the material or structure and provide the possibility to monitor internal deformation and damage in composites using an electrical resistivity method. Recent advances in both model composites as well as composite laminates have been discussed. The effect of CNT concentration and dispersion on electrical sensing behavior has also been compared and analyzed. It is worth noting that different manufacturing and dispersion processes can have a significant effect on the feasibility of industrial scale-up. Each processing route has its pros and cons, which might be suitable for a certain application. For instance, direct mixing of CNTs into low-viscosity epoxy resin may seem easy from a logistics point of view, but may result in poor dispersion, CNT alignment along the resin flow direction, and filtering effects by fiber preforms during liquid molding processes or too high viscosities for composite processing. To achieve good CNT dispersion (and localization), in situ growth of CNTs directly onto the reinforcing fiber surface or electrophoresis deposition can be performed. Unfortunately, such nanofunctionalization processes are relatively complex and costly procedures that could limit industrial applications, while there are still remaining issues regarding the preservation of fiber strength. Spray coating is an easy industrial-scalable process which has shown
to create good CNT dispersion and localization. However, when spraying nanomaterials, care needs to be taken that safety precautions are taken and that solvents are recovered in order to reduce the risk on personnel and environment. Apart from technological issues related to dispersion and localization of CNTs in composites, easy scale-up, relatively simple procedures, safety and environmental issues are among the most important aspects when considering technology transfer from laboratory to an industrial environment.

SHM requires a multidisciplinary approach, involving topics like structural mechanics, damage sensing and monitoring, electronic engineering (to process and manage signals), software engineering and statistics (to interpret data), and multi-scale composite manufacturing (to localize sensors). To obtain the best SHM results, a combination of different methods may be required. Lab-scale damage sensing concepts for composites based on CNTs to detect damage has now been around for a couple of years. Since then a number of studies have examined the potential of CNT sensing in composites, as well as interpreted obtained data to identify different failure modes. After some promising results which confirmed the potential of CNTs as an effective nanomaterial to detect damage in laminated composites, the question remains, however, how to transfer this technology into real industrial components. To progress this research area and reduce the gap to industrial applications, research needs first to demonstrate reliable and repeatable sensing data under standardized test conditions together with the development of reliable and cost-effective manufacturing methods for such multifunctional composites in an industrial environment. Subsequently, these CNT damage sensing concepts need to be tested in real components, while the information obtained from these self-sensing materials should be implemented into damage models to improve lifetime predictions of composite structures.

Figure 20  In situ damage sensing results of CNT-modified carbon fiber prepregs under Mode-I test conditions
Source: Reprint with permission from Ref. 66
| Fiber/matrix | Nanofilayers (loadings) and location | Manufacturing processes | Detected failure and damages | Main results | Standard test* (ASTM or ISO) | References |
|-------------|------------------------------------|-------------------------|-----------------------------|-------------|-------------------------------|------------|
| GF/epoxy    | MWCNTs (0.5 wt.%) in epoxy matrix  | Three-roll mill         | Delamination; microcracking  | Showed possibility of using CNTs to identify different failure modes | No          | Thostenson and Chou[49]      |
| GF/epoxy    | MWCNTs on GF surface             | Electrophoretic deposition (EPD) | Microcracking                | Coated single GF as \textit{in situ} sensor for tracking microcracks | No          | Zhang[14]                    |
| GF/epoxy    | CNTs (0.5 wt.%) in epoxy matrix  | Calendering             | Crack initiation during static and incremental tensile loading | Used CNT networks to identify different failure stages | No          | Thostenson[48, 63]          |
| GF/vinyl ester | CNTs (0.5 wt.%) in matrix     | Calendering             | Crack initiation during static and incremental tensile loading | Combined with AE, it showed some advantages of the electrical sensing method | No          | Gao LM[61]                |
| GF/epoxy    | MWCNTs (0.3 wt.%) in epoxy matrix| Calendering             | Crack initiation during tensile loading | Used CNTs to identify damage initiation | No          | Büger[64]                    |
| GF/epoxy    | SWCNT on GF surface              | Spray coating           | Microcrack initiation and propagation under tensile loading | Embedded SWCNT-coated fiber sensor provided \textit{in situ} information on resin curing and deformation under loading | No          | Luo[66]                     |
| GF/epoxy    | MWCNTs (0.5 wt.%) in epoxy      | Three-roll mill         | Localization of failure under tensile loading | Localized failure by placing electrodes at different positions | No          | No                          |
| GF/epoxy    | MWCNTs (0.5 wt.%) in epoxy      | Three-roll mill and sizing agent | Sensing under tensile loading | Improved sensing signals for CNT-modified specimen | No          | No                          |
| GF/epoxy    | CNTs (0.1/0.5/1.0 wt.%) in epoxy | Calendering             | Sensing under tensile loading | Improved sensitivity for CNT-modified CFRPs compared to neat CFRPs | Yes (Tensile) ASTM D3039 | Grammatikos[19] |
| GF/epoxy    | MWCNTs (0.5 wt.%) in epoxy matrix | Solution-based processing | Sensing under tensile loading | Alternative route utilizing aqueous CNT/polymer coating on GF for sensing | No          | Rausch and Mäder[11, 63]    |
| GF/epoxy    | MWCNTs in epoxy matrix           | Solution-based processing | Fiber breakages in dual-matrix composites | Use of CNT networks to detect fiber breakage in model sample | No          | Park JM[35, 36]             |
| GF/epoxy    | MWCNTs (0.3 wt.%) in epoxy       | Three-roll mill         | Sensing during interlaminar shear strength testing (ILSS) | In-plane sensing signals gave sudden increase at failure, while through-thickness signals showed no obvious changes during testing | Yes (ILSS) ASTM D2344 | Böger[20]                     |
| GF/epoxy    | CNTs in PVA fiber                | CNT/PVA fiber strain sensor | Strain sensing under tensile and three-point bending test conditions | Use of a CNT/PVA fiber as embedded strain sensor in GFRP | No          | Alexopoulos[8, 11, 91]       |
| GF/epoxy    | MWCNTs in epoxy matrix           | Dispersed in epoxy using sizing agent | Impact damage               | Showed potential of electrical sensing method for impact damage | No          | Gao LM[67]                  |
| GF/epoxy    | CNTs (0.1–0.5 wt.%) in epoxy matrix | Mechanical stirring and sonication | Impact damage               | Showed increased resistance after impact damage | No          | Monti[69]                   |
| GF/epoxy    | MWCNTs (0.5 wt.%) in epoxy matrix | As received             | Impact damage               | Four probes measurement provided better sensing data compared to two probes method | Yes (Impact) ASTM D7136 | Arronche[67]                  |
| Material          | Nanofillers (loadings) and location | Manufacturing processes | Detected failure and damages | Main results                                                                 | Standard test* (ASTM or ISO) | References |
|-------------------|-------------------------------------|-------------------------|------------------------------|-------------------------------------------------------------------------------|-----------------------------|------------|
| GF/epoxy GF/epoxy | CNTs (0.1–1.0 wt.%) in epoxy matrix | Three-roll mill          | Open hole and impact damage | Applied electrical sensing method to large composite plates                   |                             |            |
| GF/epoxy GF/epoxy | MWCNTs in epoxy                     | Solution-based processing| Sensing under tensile, cyclic tensile fatigue, and impact | Compared effect of sizing and treatment of CNTs with improved dispersion leading to better sensing signals | Yes (Impact) ASTM D7136             |            |
| GF/epoxy GF/epoxy | MWCNTs (0.5 wt.%) on GF surface     | Dip coating              | Single glass fiber with coated CNTs as multifunctional sensor | First time coating of CNTs onto GF for sensing rather than mixing into matrix | No                           | Gao SL     |
| GF/epoxy GF/epoxy | MWCNTs on GF                        | Spray coating            | Delamination and interlaminar shear | First time use of spray coating to deposit CNTs in GFRPs, introduced percolated network for damage sensing with extremely low CNT content | Yes (DCB, SBS) ASTM D5528, ASTM D2344 | Zhang      |
| GF/epoxy GF/epoxy | MWCNTs (0.047 wt.%) on CF prepregs  | Spray coating            | Delamination                  | Showned correlation between electrical sensing signals and force drop, and improved sensing stability | Yes (DCB) ASTM D5528          |            |
| GF/epoxy GF/epoxy | CNT thread                          | Embedded fiber           | Matrix cracking               | Use of CNT thread as embedded sensor in GFRPs for damage detection            | No                           | Hehn       |
| GF/epoxy GF/epoxy | MWCNTs (0.08 wt.%) on CF            | Spray coating            | Interlaminar shear            | Demonstrated progressive damage sensing with through-thickness measurements   | Yes (SBS) ASTM D2344 No      | Zhang      |
| GF/epoxy GF/epoxy | CNT (0.5 wt.%)                      | Sonication               | Fatigue                       | Correlation between electrical sensing results and AE signals under fatigue mechanical testing |                             | Grammatikos |
| GF/epoxy GF/epoxy | CNT/Al₂O₃ (0.5 wt.%)                | Three-roll mill          | Sensing under tensile loading | Use of CNT/Al₂O₃ as conductive filler in epoxy to detect damage               | Yes (Tensile) ASTM D3039 No | Li         |
| GF/epoxy GF/epoxy | CNT growth on GF                    | Embedded fiber           | Sensing under tensile loading | Use of fuzzy glass fiber as strain sensor in CF prepreg                       |                             | Sebastian   |

*Standard testing in this table indicated that both specimen dimension and test conditions were according to test standard.
Conflicts of interest

No potential conflict of interest was reported by the authors.

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