Chapter 11

Damage Detection and Critical Failure Prevention of Composites

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Additional information is available at the end of the chapter

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Abstract

In this chapter, critical failure prevention mechanism for composite material systems is investigated. This chapter introduces both non-destructive failure detection methods and live structural tests and its applications. The investigation begins by presenting a brief review and analysis of current non-destructive failure detection methods. The work proceeds to investigate novel live structural tests, tomography and applications of the proposed techniques.

Keywords: critical analysis, composites, smart materials, printed circuit board (PCB), damage detection

1. Introduction

Failure detection methods of carbon composite material systems are currently the subject of much research effort in the composite material community at large; see, for example [1–4], using a variety of failure detection methods and control algorithms. For enhanced reliability, early failure detection methods with critical failure prevention are preferable. Therefore, early failure detection techniques have become increasingly popular in the composite material systems community. Live failure detection techniques in composite material systems offer a structured approach to resolve failure-related issues giving essential early indication and warning. In this chapter, details of live failure detection techniques will be discussed in addition a brief review and analysis of current non-destructive failure detection methods of composite materials.

It is necessary to review current failure detection methods and determine if any of these methods have the potential to be used on low cost consumer products with scope for high end specialised equipment. This will determine if there is a potential technology gap that if filled will have a significant advantage to the consumer and specialist that can determine the state of health of equipment commonly in use. For this to be successful, the solution must be cost effective, robust, require low damage inspection knowledge and skills and be readily available.

There are a number of common causes for damage to occur and it can be certain that once there is a damage this will perpetuate further. The damage of a composite and its components can be attributed to different stages in their life: during manufacture, construction and the in-service life of the composite. A matrix crack typically occurs where there has been a high stress concentration or can be associated with thermal shrinkage during manufacture, especially with the more brittle high-temperature adhesives. Debonding occurs when an adhesive stops adhering to an adherend or substrate material. Debonding occurs if the physical, chemical or mechanical forces that hold the bond together are broken. Delamination is a failure in a laminate, often a composite, which leads to separation of the layers of reinforcement or plies. Delamination failure can be of several types, such as fracture within the adhesive or resin, fracture within the reinforcement or debonding of the resin from the reinforcement [3].

A void or blister is a pore that remains unoccupied in a composite material. A void is typically the result of an imperfection from the processing of the material and is generally deemed undesirable. Because a void is non-uniform in a composite material, it can affect the mechanical properties and lifespan [5]. Blisters are generated in the outermost layers. Porosity can be caused by volatile entrapment during the curing of the resin.

Wrinkles are common when adding new layers; it is significant to eliminate them as they can weaken the composite [6]. The inclusion of foreign bodies in the composites can include backing film, grease, dirt, hair and finger prints, which can lead to areas rich or deprived of resin [7]. To avoid the occurrence of a catastrophic failure due to manufacturing defects, impacts or fatigue damage, critical structural components are regularly inspected using various non-destructive testing methods.

The visual inspection is the most basic type of non-destructive testing method for composites [8]. Another quick and easy method for detecting exposed carbon fibres is to run a dry cloth over the surface as the fibres become easily snagged on damaged parts of the structure due to exposed fibres, this is immediately apparent to the inspector [9].

To increase the chances of visual inspection, a force may be applied to the structure acting as a manual flex test, which would further open up any cracks making it more likely to be seen. However, if proper care is not taken with this approach, it is possible that the carbon fibre can be excessively flexed beyond its damaged capabilities and incurs additional damages. The tap test is another simple test that can be performed as part of routine maintenance [10]. However, this technique is highly operator dependent as it requires a ‘feel’ for how it is meant to sound [11].

Radiography type testing uses X-ray and gamma rays for detecting internal imperfections or defects [12]. Ultrasonic inspection works by sending a high frequency sound wave into the structure and then measuring the reflected sound wave. The amount of energy transmitted or received and the time the energy received is analysed to determine the presence of flaws [13]. Dye penetrant method [4] can be used to detect the materials surface defects, but as it can only reveal surface defects and does not give details of depth of defects, it can also be difficult to test coarse surfaces. Pulse thermography [14] is an advanced non-destructive testing method, in this method thermal imaging cameras are used to detect material failures [15].

Acoustic method [12] is a structural health condition monitoring method which can be used for continuous monitoring of in-service structural components and help increase confidence regarding the remaining in-service lifetime if a fatigue limit cannot be defined easily. This method refers to the generation of transient elastic waves that are created by sudden redistribution of stress in a material. When the material is subjected to a change in pressure, load or temperature localised sources trigger the release of energy. The energy released is in the form of stress waves which propagate through the material and to the surface. It is possible to observe such stresses with suitable sensors mounted on the material. In composite materials, it is feasible to monitor for matrix cracks, fibre breaks and debonding.

Eddy current testing uses a circular current to detect the presence of cracks, surface breakings and variations in the composition of materials as well as identifying the material itself. It is an electromagnet testing which is one of the oldest testing methods [16]. However, its limitations are that only electrically conductive materials can be inspected, the surface must be accessible to the probe, an excellent level of inspector training and experience is required, rough finishes can interfere with the test, depth of penetration is limited and it is not suited towards large area testing.

A review of reported non-destructive testing methods for failure detection and prevention shows that many approaches require the composite structure either be taken to a test house or that relatively complex and large equipment be taken to the structure site [9]. In each case the equipment is large, requires a high level of competence and is typically expensive. Furthermore, the range of defects is wide and so requires advanced techniques to detect their presence, which leads to the development of live failure techniques in composite materials.

2. Design innovation

It is understood that there is a requirement in a relatively unexplored area that can be broadly classified as live failure techniques in composite materials. Continuing with carbon fibre as the material of interest, it is necessary to investigate various methods of resolving issues currently unsolved. Design innovation is intended to provide a structured approach to resolve such issues with clear and guided paths for which the theoretical solutions can be documented, analysed, assessed, researched and progressed through feasibility studies and ultimately development and prototyping of the product. Such an approach gives alternative direction and multiple concepts should a particular theoretical solution have a shortcoming or worst case fail to deliver on its targets. With several theoretical concept solutions documented and assessed for practical feasibility, we can continue to progress into a practical environment and begin the early stages of product development.

It is prudent in such an application as critical failure of composites to have a reference point in which to determine the successfulness of a proposed live failure system. For this reason, the first step before commencing works on a practical solution is to develop and document working procedures for the creation of test subjects or specimens, in this case small samples (batches) of carbon fibre specimens. Progressing on with this methodology, similar procedures were again developed and documented for stress testing carbon sample specimens. This gives a solid foundation in the form of controlled test specimens along with quantised data in which implementations of the theoretical concept solutions can be applied and importantly evaluated against and thus measured for success.

2.1. Control structure

The control specimens comprise of a small strip of 430 g 2/2 twill vari preg carbon fibre with the dimension 30 × 300 mm, these are four layer plies of identical ply orientation. The samples are cured in a preheated environmental chamber set at 100°C for 90 min which conforms to the guidelines on the carbon fibre vari preg data sheet supplied by the manufacturer. The control structure is set at these parameters as it allows for relatively fast builds due to the low ply count and is of suitable size for structural tests, the low dimensions also gives minimal manual labour when applying the proposed theoretical concept solutions for the failure detection methods already set out in the design innovation phase. It is essential that such rapid builds are possible due to the necessity to test destruction for each sample specimen in order to observe its behaviour when no foreign bodies are included. This is an essential requirement as additions that will be added later such as sensors or probes, for example, must not compromise the structural integrity of the composite which could actually lead to a lower strength composite material. To reiterate, it is considered desirable that any proposed early detection method do not impose a penalty in terms of the composites structural strength as it would be prior to the application of the detection system.

A small control sample batch of 10 units (specimens) is produced and logged, the higher the quantity of the control sample batch will increase the comparison accuracy of subsequent batches that are fitted with the failure detection system. The exact number of batch quantities lies with the project size and desired test plans. In this case, it was deemed more appropriate to run smaller samples during the initial concept phase of the project where the failure detection method was likely to be frequently altered. When the failure detection system is proved suitable for its intended operation at a more mature time during its development, then the batch size will be increased as only refinements will be necessary at this stage. This scaled approach allows for rapid prototyping that leads onto a slower polished version as the direction becomes more apparent from the research activities.

Each individual control sample specimen was analysed and the data logged. Flexural tests on each sample were conducted using the universal testing machine (see **Figure 1**). In the image, it can be seen that we have two points supporting the control specimen of carbon fibre and epoxy resin composite, the third point is applied from above and applies the deformation on the sample. The test is automatically monitored by a personal computer that records the deformation distance in millimetres and the force in Newton, from this a graph can be plotted.

Individual data analysis logs details such as the sample specimen weight. The mean values, variance and standard deviation are calculated with the accompanying formula. This gives

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Figure 1. Flexural test equipment: universal testing machine.

a quick to view reference point that can be easily remembered and referenced against for future builds that utilise a damage detection technique and can give indication to how much the damage detection system has altered the properties of the native carbon fibre composite.

Figure 2 shows key characteristics of the control sample specimens tested with the flexural test setup on the universal testing machine. Collective data results of the three point flexural test are shown in **Figure 3**.

Referring back to **Figure 2**, the graph shows the data recorded for specimen 8 of the control batch with regions of interest highlighted. It can be seen that the sample initially operates in its linear and elastic range as expected. The first potential sign of damage is at a deformation of approximately 16 mm and this can be seen as 'elastic but no longer linear' on the graph. This first sign of damage and could be heard as a low volume audible crack from the carbon fibre. Under visual observations absolutely no damage was observed. Increasing deformation to 19 mm equating to 215 N, a second crack is heard with increased volume and a noticeable movement in the carbon fibre was observed as the curvature of the sample marginally straightened from the test point. At this point, visual observations failed to recognise actual surface damage, it is assumed, however, that removing the specimen from the test machine at this point would reveal a permanent deformation in the specimen that was originally entirely flat. From this deformation point onwards appreciable crackling could be heard as the matrix and reinforcement broke down. It was only at the fracture point that it was apparent that the composite had failed but was still bound by the fibres in such a way that it was still an intact single piece of carbon composite. Ideally, a failure detection technique would be able to monitor damage when the material has gone beyond its linear and elastic range as this would give the maximum possible time to the user that the composite was approaching failure. Due the sensitivity required to detect this minuscule disturbance (which was not present across all control sample specimens tested), it is considered more appropriate to detect the region of yield strength where stronger indications of damage occur. It is assumed that if an alert can

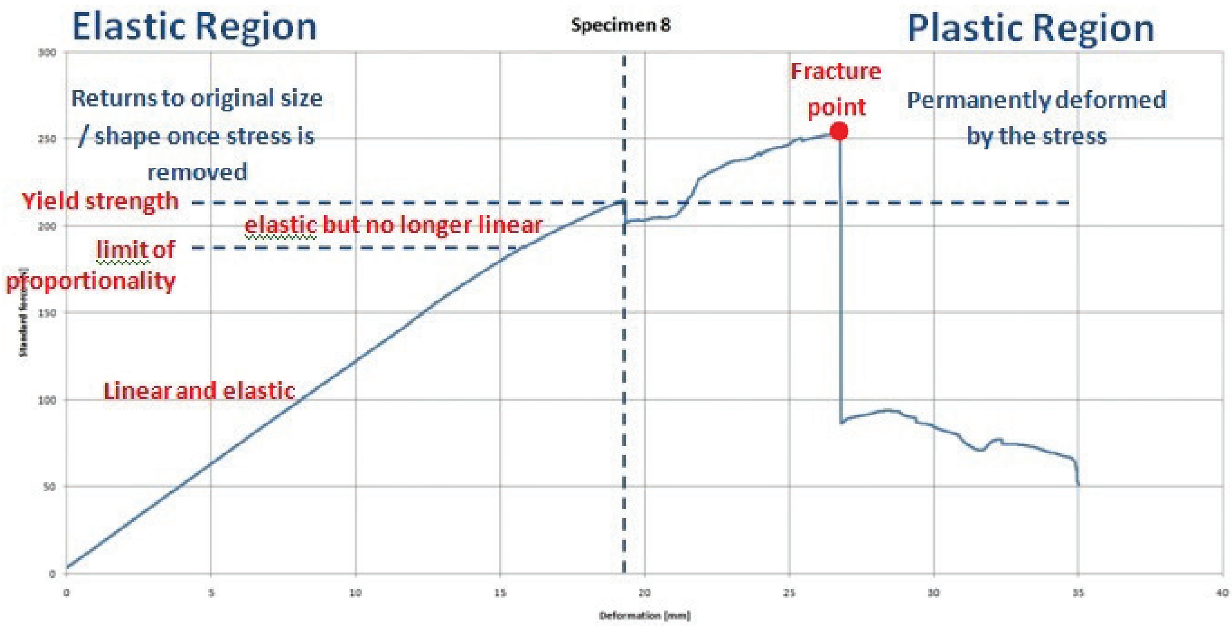

Figure 2. Control sample specimen.

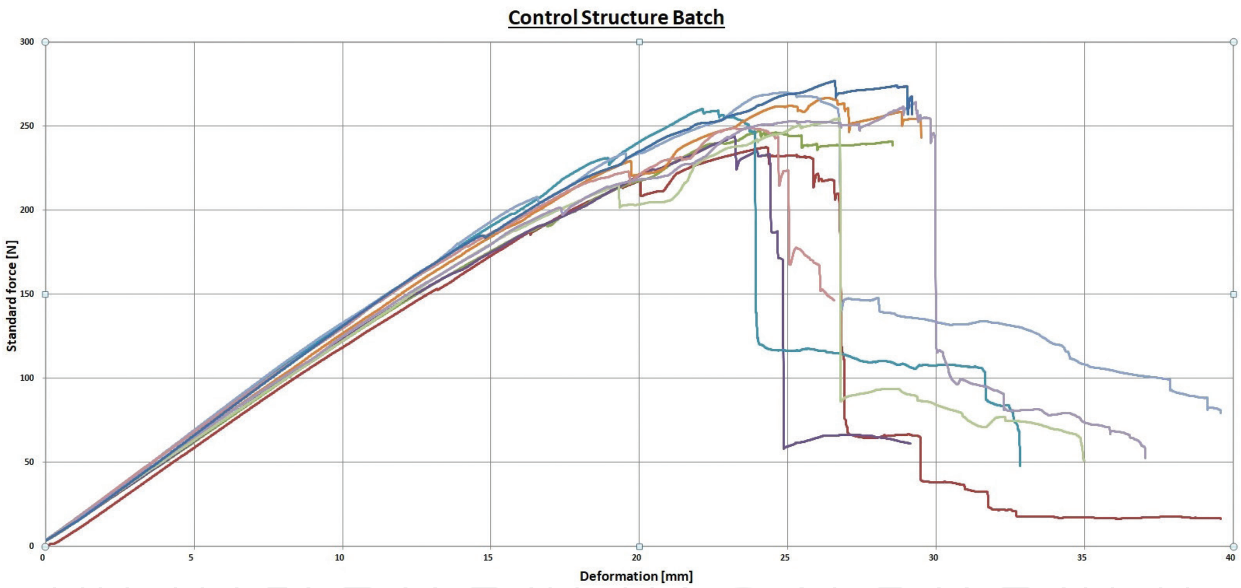

Figure 3. Collective data of three point flexural test.

be issued to the operator of the structure (e.g. bicycle) at this point that enough prior warning has been given to be able to come to a safe stop and have the structure assessed by more in depth damage detection equipment such as X-ray.

These issues occur in many different applications. In this section two examples are discussed, firstly a bicycle application and then a quadcopter application.

Graphs are recorded and analysed on an individual basis but can be seen collectively (see **Figure 3**) for the three point flexural test: The Y-axis represents the force in Newton and the

X-axis is the deformation in millimetres. Observations show that each sample follows a similar trend but can vary at its key parameters such as fracture point, etc.

The mean weight of each sample is 26.37 g and this is a good indicator to the amount of material used in the sample (carbon fibre and epoxy resin), it can be helpful to reference this as to gauge consistency of the manual work during the construction of the sample specimens. Other parameters and their associated equations can be seen below:

- Weight (variance):

$$\sigma^2 = \frac{\sum x^2 - \frac{(\sum x)^2}{N}}{N} = 0.15\ g \tag{1}$$

Control specimen weight variance of 0.15 g from a mean value of 26.37 g.

- Peak force (variance):

$$\sigma^2 = \frac{\sum x^2 - \frac{(\sum x)^2}{N}}{N} = 133.8\ \mathrm{N} \tag{2}$$

Control specimen peak force variance of 133.8 N from a mean value of 255.9 N.

- Yield strength (variance):

$$\sigma^2 = \frac{\sum x^2 - \frac{(\sum x)^2}{N}}{N} = 40.41\ \mathrm{GPa} \tag{3}$$

Control specimen yield strength variance of 40.41 GPa from a mean value of 192.3 GPa.

Although bicycle applications are relatively safe, as they categorised in the land section of applications, many serious accidents do occur from continued use as the rider is unaware that the structure has been pushed past its performance envelope. Life-threatening events are more likely to occur in aviation structures such as planes if this were to go undetected. Although arguably impossible to come to a gradual stop in such a situation, if the pilot were alerted to such detection it would be possible to 'limp home', where by the aircraft would be restricted to low G movements such as turns or deceleration. Unexpectedly similar risks can be expected in unmanned aircraft or the ever increasingly popular quadcopters or drones. Although no immediate threat of life is assumed due to the lack of an onboard pilot, drones are increasingly flown in areas of large crowds due to their ability to carry high end photography equipment. It is no longer uncommon for higher end drones to approach 10 kg in weight and exceed this, due to large professional cameras for photography and film industry. It is therefore appreciated that the risk of life would be to the crowds immediately below should damage be undetected to one of the motor arms resulting in a complete lack of vertical thrust.

2.2. Mesh structure

To satisfy the requirements of live failure detection systems at its most basic level was to incorporate what was deemed as the simplest concept solution being the 'mesh structure concept'. For this two options are available, in the first instance a simple conductive mesh with insulating material is embedded within the carbon plies (**Figure 5**, left image), this thin diameter mesh was constructed of low gauge enamelled copper wire with a diameter of 0.22 mm and applied to the inner plies of the carbon fibre stack before curing. The mesh wires are allowed to extrude from the carbon fibre as flying leads from which simple test equipment can be attached such as a multimeter. Currently, the mesh is created from a single piece of wire which gives two open-ended flying leads, this offers the most simple and rapid technique to embed the mesh for research purposes. The mesh, however, is not limited to this single wire as it is possible to use multiple wires with the advantage of a means of simple damage location, however, this introduces greater complexity and additional electronic hardware to monitor the system, it is still an uncomplicated method. Arguably the requirement for multiple wire systems are not essential for simple carbon fibre constructs nevertheless it does give a factor of flexibility should the design constraints demand more precise failure detection which requires location data.

Details of the different applications in simple and complex structures will be explained later. However, in order to explain the mesh structure in detail, in this section, the quadcopter application within the aeronautical sector (see **Table 1**) is considered.

The mesh structure can be more easily understood with reference to the quadcopter CAD diagram (see, **Figure 4**, right image). In this case, the quadcopter frame is constructed of glass reinforced epoxy laminate (FR4) more commonly used in printed circuit board (PCB) manufacturing. It is a composite material comprised of a flame resistant [17, 18] woven fibreglass cloth and an epoxy resin binder. It can be seen that the front half of the quadcopter frame (upper area) has no failure detection system incorporated, whereas the rear half (lower area) has the basic level of failure detection integrated onto the FR4 board (see **Figure 4**). This simply includes a single track of copper at 1 oz. which equates to an approximate thickness of 0.089 mm. At the rear (centre lower area) of the frame are two pads in which suitable electronics can be connected in order to monitor that the wire mesh has not gone open circuit as a result of physical damage such as a fracture, for example. This monitoring signal can be fed to the flight controller and transmitted to the user via flight telemetry data. It is almost effortless to separate the wiring for each arm if damage location is to be realised, giving an adequate enhancement if the user requires data as to know which quadcopter arm has sustained physical damaged. The diagram shows the failure detection method as a red line (copper PCB trace), this has been applied to the upper layer of the PCB to allow for a visual demonstration

Catagory	Example 1	Example 2	Example 3	Example 4
Aeronautical	Aircraft	Aerospace	Unmanned ariel vehicles	Drone taxi
Land	Formula 1	Cars	Bikes	Composite wheels
Nautical	Submersibles	Hulls	Yacht masts	Booms
Leisure	Bicycles	Golf clubs	Windsurf masts	Rackets
Business	Security	Dispatch	Wind turbine blades	Architecture
Military	Combat vehicles	Armoured vehicles	Essential electronics	Fighter jets

Table 1. Application list examples.

Figure 4. Traditional drone frame (left), enhanced NDT CAD frame (right).

of the system, however, it is possible to incorporate this to the inner layers or bottom of the board as desired by the designer. It is easy to realise the simplicity and the benefits of this approach especially when compared to the available quadcopter frames currently on the market as shown in **Figure 4** (left image). Here the veined arms reduce weight but shows obvious risks of catastrophic failure should a single element be damaged and go undetected.

PCBs are readily available in various thicknesses, multiple materials and layer makeup's offering an applicable solution for a variety of applications. Increased thickness of the FR4 board improves rigidity whilst a lower thickness improves flexibility allowing for lower FR4 thicknesses of 0.4 mm to be curved around existing structures such as carbon fibre. It should be noted that appropriate adhesion be applied spanning the entire FR4 board as poor contact can allow fractures in the hosts structural material not to propagate to the FR4 failure detection board. Additional precautions should be noted as the addition of two different composites simply stuck together brings potential problems due to differing mechanical properties inherent with the constituent composites. As an example, the Young's modulus of standard carbon fibre is 70 GPa where FR4 is 24 GPa, similarly thermal expansion coefficient variance would be of concern at temperature ranges if the individual composites were not suitably decoupled. It may be considered suitable in certain situations and this is left to the engineer to utilise appropriate combinations of composites for the environment and that of the host structure.

In the second instance, the wire mesh can be added as an aftermarket product to existing carbon fibre structures or even non-conductive structures such as fibre glass. This would typically be applied as a single unit, fixing a mesh as a single wire to structures can be labour intensive and cumbersome. It is, therefore, more appropriate to have the mesh incorporated on an adhesive sticker and applied by normal manufacturing routes.

The benefit of the mesh structure is that the detection electronic hardware is extremely simple, requires very low real estate of the host structure and its operational power consumption is almost negligible, lending itself perfectly to long-lasting portable applications. Further, more such a system can be powered by energy harvesting methods such as vibrations, solar, wind and the like, this will obviously incur additional constraints in terms of size and cost of the overall damage detection product. The detection principle is a simple case of measuring current flow through the conductive copper mesh, when damage occurs as a result of a crack or over flex in the structure then the conductive wire is severed ceasing current flow, allowing the user to be alerted to the fault. Such a simple solution has its draw backs and this is the location accuracy to the damaged area. In preliminary lab tests on wire mesh test specimens only ~50% of flexural test fractures were detected before a catastrophic failure event. Analysis shows that the reason for this was down to one of two reasons; either the mesh wire was not present in the fracture line or that the fracture width was not great enough to be detected. The image (see **Figure 5**) is taken at ×200 magnification of a mesh structure specimen:

Observations show that the 0.22 mm enamelled copper wire has stretched with the fracture during flexural testing, ideally, this would have sheared and broke at the same rate as the carbon fibre. To improve the system, it is suggested that the detection material to have a similar Young's modulus to that of the material under test and that a suitable pitch be used for the mesh to be fitting to that of the application. However, this method has proved an extremely low cost and portable method for additional safety where there was none. The application has been used in low cost multirotor (quadcopter) frames in particular the motor arms where damage could be incurred from in-flight collisions such as trees, buildings and the like. This gives an entry level of security against further damage should such a collision occur and the operator continue to fly the multirotor, as without being immediately able to inspect for damage such damage is unknown.

2.3. Wafer structure

The sheet structure method utilises an insulating material as alternating ply layers with the carbon fibre plies to make the stack. In this concept specimen absorbent glass mat (AGM) is implemented which originates in lead acid batteries [19]. The AGM is reduced in thickness to a depth of approximately 1 mm and is sandwiched between the pre preg carbon fibre sheets. For example, the ply make up would consist of a first ply being carbon fibre, the second ply AGM, the third ply carbon fibre, and so forth until the desired layer make up is achieved. The theoretical objective behind this makeup is to monitor electrical conductivity between the now mostly electrically isolated plies of alternating carbon fibre, such as layer one and three, to continue the example mentioned above. When the alternating ply stack of carbon fibre and fibre glass is damaged the strands break and combine into a fibrous blend

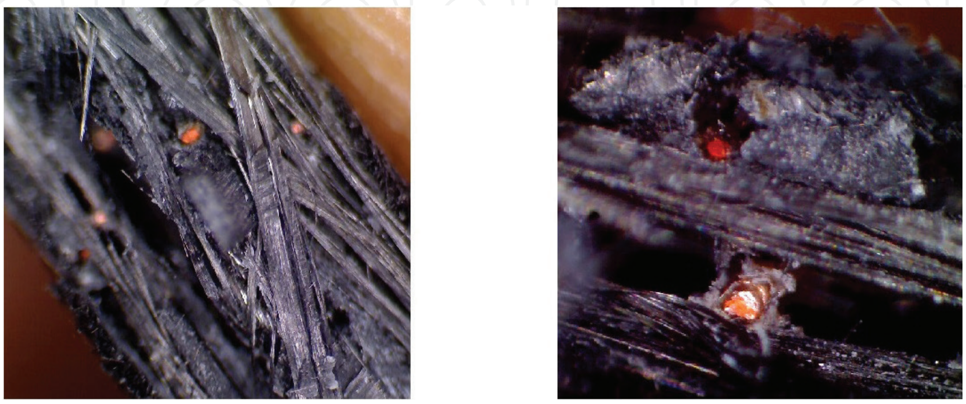

Figure 5. Tapering of conductive mesh (up to ×200 magnification).

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causing measureable electrical conductivity between the pre damaged isolated plies, therefore can be measured with simple portable electronic equipment. In practice the layers are not 100% isolated and the AGM caused the structure to fail more rapidly during flexural testing. It is predicted that longer glass fibres be used as the insulating material to provide increased structural integrity, or an alternative insulating material be used such as Kevlar, consideration should be given to Kevlar as it is absorbent to water. Caution should be taken as to the expansion properties of each constituent material and suitable proof of concept works is required to ensure the hybrid composite performs as desired. It is fair to assume that this approach would be a trade off or compromise to a pure carbon fibre composite. However at this time full laboratory testing has not been completed and the full benefits or disbenefits of such an approach is unproven, it is possible that other mixtures of plies can offer significant advantages over that of carbon fibre alone for certain applications such as fire retardant improvements.

3. Experimental study

Current research takes onboard a known technique that has been practiced for many years, possibly the earliest is the X-ray computed tomography, well known as the CT or CAT scan [20]. Similarly, a geophysical monitoring method known as electrical resistivity imaging or ERI typically uses four equidistant electrodes such as metal probes that are staked into the ground. Two of the four probes are used to induce a low frequency or direct current into the earth and the remaining two probes are voltage or potential probes which measure the resultant voltage potential. The voltage is simply converted into a resistance value that represents an average resistance between the probes, this method is often found in archaeology [21].

Another approach that is widely researched and utilised in the medical field is known as electrical impedance tomography (EIT) [22–23], surface electrodes usually physically organised in a ring layout are in direct contact with the skin, generally with electrocardiogram (ECG) electrodes and gel to improve conductivity. This is then positioned, for example, around the chest or leg and a small current is passed through the ECG probes whilst the passive ECG probes measure resistance and reactance, similar to other tomography techniques. The resultant post-processed image represents the phase shift in the measured signal depending on the technique used. The probe count is typically higher in comparison to other fields such as geological tomography to provide an increase in resolution of the image, 16 electrodes and higher is not uncommon. When a measurement has been taken electrodes are rotated until the full electrode array has been sampled, the resulting data is processed and the cycle begins again.

There are many types of electrical tomography but all are based on the same principle. The intention of which is to construct an image from a physical object of its observed measurements. As such this is an inverse problem and is one of the most important and well-studied mathematics problems in science and mathematics today [24]. The direct problem is relatively undemanding, the inverse one is particularly difficult.

Any solution to an inverse problem requires an element of estimation to fill in data that is not available and as such any solution cannot be void of resolution error or may be low of resolution. However, such techniques do provide suitable representations of the object in question and is a technological step forward.

With reference to **Figure 6**, the left most image labelled 'carbon fibre' shows the physical test setup of the embedded probes (electrodes) and the highlighted damaged area shown within red circle, where as the right image 'EIT image' shows a typical result from post-processing. It may be difficult to see damage to the physical carbon fibre structure visually due to the surface ply remaining intact; the EIT technique can also provide useful insight to the structural health of the composite.

Although the technique provides a solution for carbon fibre, various problems need to be addressed in order to deliver a suitable end product for mobile live applications. Consequently, fast processing of data is required with little computational overhead whilst maintaining suitable resolution for adequate damage detection. In addition omissions need to be made for any flex in the structure as this varies the structures electrical resistivity and can be mistakenly characterised as damage if the implemented algorithms are not accurate. Further exacerbating the situation, environmental conditions play a large role, temperature changes are picked up by the same technique used to detect damage due to the temperature coefficient of the composite material. The resultant solution to the problem of creating a portable live damage detection system must address each mentioned issue successfully if such an inverse problem is to be of practical use.

However, techniques such as tomography is widely in use today within various scientific fields and do offer a solution to where there was none. The additional problems mentioned such as resistance changes due to flex and the environment such as rain and sunlight causing localised temperature changes can be addressed with hardware or software implementations. At its fundamental level these challenges ultimately reduce the sensitivity of the tomography technique in composites and its effectiveness of detecting structural health conditions. As such, future research is required and ultimately real world testing of hardware and software algorithms to determine if this method is adequate across all applications.

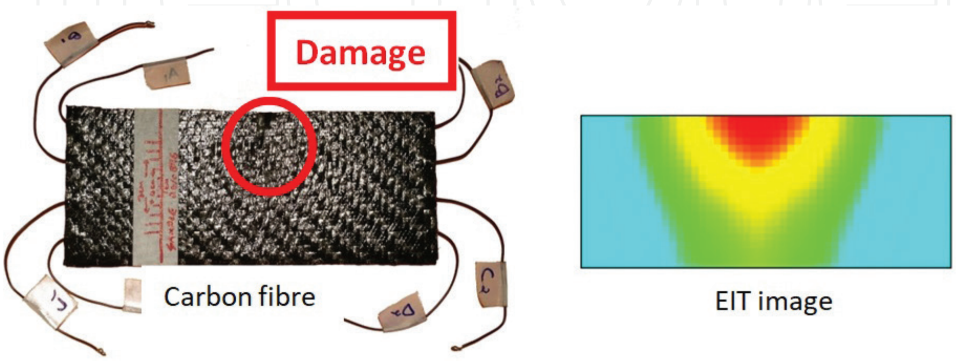

Figure 6. Test specimen & electrodes (left), expected EIT image (right).

4. Applications

There are many applications in which the suggested damage detection methods mentioned can be utilised in which no prior solution has been achieved other than offline methods, such offline methods require the structure in question be taken to a test laboratory for a skilled professional to access. Although the suggested methods are still progressing through the research phase and have yet to be formalised, such as production methods and materials for the mesh method, wafer method and the experimental method based on tomography technique, **Table 1** shows a list of potential applications for the concept techniques described.

The potential applications for online damage detection are arguably limitless and the table demonstrates the range of applications to illustrate this. The proposed concept methods include both forward and inverse problems of the mesh and tomography techniques, respectively. This allows a suitable system to be used depending on the requirements. Some of the less obvious applications mentioned that have not been covered already are discussed for clarification and completeness.

For the application of military damage detection, is it not uncommon for vehicles and associated parts to come under gun fire or explosive blasts, it is difficult if not impossible to assess the damage from within the relative safety of the vehicle. Although the vehicles are generally not constructed of carbon fibre but of metals or composites such as steel and ceramic it is possible to address the issue with the mesh technique. Thin sheets of mesh can be attached in suitable key locations behind the armour plating for detection of a breach in the vehicles structure. This would be of particular importance if essential drive train components or tactical equipment were present at this location. To enhance the detection further printed circuit boards can have an additional layer within the FR4 substrate or as an addition to the top or bottom layers that can act as the mesh damage detection, similar to the quadcopter CAD diagram (see **Figure 4**). This can give essential feedback to the vehicle users should an electronic system fail due to projectile damage from such gunfire or explosive devices.

5. Discussion and concluding remarks

In this chapter, a brief overview of carbon fibre has been given along with its common defects and the conventional non-destructive testing techniques. This basic ground work establishes the direction of current research and why the concept methods were chosen. This progresses to a simple overview of the design innovation approach and initial testing stages and comparison methods involving control specimens. A table of its intended applications are given to give an appreciation of the flexibility of the proposed end products that can be developed as a direct research outputs. To date there are no suitable live detection techniques available that can provide a portable solution for low cost consumer products or high end equipment in an easy to install manner.

The design innovation and research approach taken in this study has allowed for the potential development of flexible methodologies and products. The methodology as demonstrated in the mesh technique on the quadcopter may be taken immediately into existing designs such as PCBs for physical damage detection at a cost of adding an existing layer to the design, alternatively this can be routed into the existing layer should it be suitable. An advanced understanding of PCB design may be desirable as the effects of broken ground planes and radio frequency wave interference could result if the mesh technique is not correctly implemented. Any one skilled in the art can adopt such a methodology without adverse effects to the original design. This most basic level of damage detection is extremely low cost and simple to implement, the simplicity allows for a robust detection system that requires no processing power and is considered mechanical in its design. There are various ways in which this method can be practiced and the only limitation is that of the designer. Research is still continuing in this area to expand upon the range of applications, its successfulness in detecting damage and the operating margin at which the damage is detected.

Increasing in technological difficulty is the wafer technique which relies upon alternating conductive and insulating plies. This is another mechanical method and is a forward problem like the mesh concept, therefore offering a simplistic solution and inherent robustness within the design. Although the works are in its early stages it can be appreciated that only certain materials may be of interest for this to be successful. For example, it is necessary for a conductive ply material and non-conductive ply material to make up the stack, at minimal a three ply stack would be necessary. Unlike conventional composites where there is typically only one reinforcement material there would now be two but the matrix in current research motioned in the text has been kept at one and is a polymer resin. It is worth mentioning that this is not considered a hybrid material as these are composites commonly using one organic and one inorganic compound at the nanometre or molecular level. However, this does bring an alternative possibility and research route for hybrid material design specifically targeted for damage detection. The undersized research effort concentrated on this technique has been investigated on traditional carbon fibre and an experimental material of AGM. As previously mentioned in the chapter, the relatively short fibres of the AGM had such a negative effect on the strength of the structure that no further tests were carried out. Research efforts will continue in this area on traditional fibre glass sheets as used in composites to increase structural integrity. It can be appreciated that this will not be as strong if only carbon fibre was used as a single material but this would be a known sacrifice for the damage detection system should it prove adequate.

Finally, the experimental technique involves the tomography approach, although this technique is approached by many in the research community there is yet to be of any commercial products available that exploits its use in commercial composite structures. This approach is considered advanced due to the inverse problem and potentially difficult to implement in practical applications. In lab tests in a controlled environment, it is relatively simple to implement and offers suitable detection of damage, bench tests were conducted on physically small specimens with advanced equipment. The damage detection values are of such sensitive levels that it may be difficult to engineer the electronic circuitry required for portable applications requiring low power consumption with today's technology. Under the bench test conditions heat changes to the composite due to manual handling were detected as damage, this was also true of temperature changes from air conditioning units being switched on or off. The effectiveness of this method can never be absolute due to the inverse problem and this is exacerbated by the need to mask temperature drift and sudden changes of the composite. The actual value of this technique as such will not be realised until fully inspected.

Collectively a broad spectrum of novel techniques and methods have been conceptualised within the three categories mentioned in this chapter with a comprehensively range of technical difficulty. Continued research is required to prove the effectiveness in practical applications and can only be realised with future efforts. The ultimate goal of which is to develop a new range of products and methods that can give early warning and/or locations of physically damaged structures or components that comprise of systems that would cause further injury or critical failure if left undetected in use.

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