NDT METHODS FOR EVALUATING CARBON FIBER COMPOSITES

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Abstract

A review of nondestructive testing methods is presented and their potentiality for monitoring composites, undergoing fatigue testing, in realtime is discussed. Fatigue testing of composites can take very long time, up to several weeks. The purpose of monitoring is to detect incipient faults and to predict the remaining fatigue strength of the composite. If the predicted number of cycles-to-failure is unacceptable, the test can be stopped and considerable time saved. Two approaches stand out: methods based on acoustic emission and the electrical properties of composites. The potential of these two methods is discussed in greater detail.

Keywords: NDE, NDT, Fatigue testing, Carbon Fiber Composites, Acoustic Emission, Electrical properties.

1 Introduction

Testing methods can be roughly divided into two groups depending on their purpose. The first group consists of methods that are used for determining material properties and they are most often destructive. The second group, on the other hand, contains nondestructive methods which are used for condition evaluation.

Material properties are important for engineers. In order to be able to select the right material and carry out calculations during the design process, reliable properties must be available. Many material properties are found by damaging samples of a material in standardized tests. Examples of such properties include: hardness, tensile strength, Young’s modulus, Impact strength, fatigue characteristics, corrosion resistance, UV-stability and more. Many properties are dependant on temperature and therefore their behavior at different temperatures must also be known. Even though this information is vital for the design process, it isn’t always sufficient for determining how the product will perform when put to use. The reasons for this can be due to theoretical limitations and the fact that standardized tests do not completely determine the material properties. This is especially relevant for new material types such as composites. Therefore, during the design process prototypes must be built and tested in order to see if the design fulfills the requirements.

Even though a product passes all tests and requirements, quality inspection tests must also be performed. The need for monitoring does not end after the product has been sold, in fact it needs regular inspection while in service. The inspection methods can vary, depending on the product and its usage. Most are satisfied with inspecting their home appliances by trying them. However, few are willing to fly in an aeroplane that is tested by such inspection methods. It can therefore be said that the extent of the inspection is proportional to risk and cost.

This paper provides a review of methods for nondestructive testing. The review is aimed at identifying testing methods that can be used for realtime condition monitoring of composites undergoing fatigue testing. The purpose of condition monitoring is to detect incipient faults and predict the remaining fatigue strength of the composite, i.e. the number of cycles-to-failure. Because many nondestructive testing methods utilize some material properties, an overview of carbon fibers and carbon fiber composites is necessary. Section 2 gives an overview of carbon fibers, their properties and the types of faults/damages that can be found in composites. Section 3 starts with a brief review of the main nondestructive testing methods for carbon fiber composites and then two NDT methods who are believed to be more suitable for use with fatigue testing are
discussed in greater detail. These two methods measure Acoustic Emission signals and electrical properties of the composites. The paper concludes with some final remarks and comments.

2 Carbon Fiber Composites

Approximately 80 years passed from when Sir Joseph Wilson Swan, in 1878, and Thomas Alva Edison, in 1879, independently produced incandescent lamps with carbon filaments [1] to when carbon fibers became a commercial product. The need for lighter and more heat resistant building material for the military and space applications was the main reason for increasing interest in carbon fibers [2, 3]. The interest was an impetus for improving production methods [4] which in turn made it possible to manufacture cheaper fibers. As a result of this, general demand increased. According to the AMPTIAC\footnote{1} newsletter, figures released from SACMA\footnote{2} show that the world demand increased from 5.850 tons in the year 1991 to 10.368 tons in the year 1998. The figures are based on production numbers from SACMA members who are believed to stand for 85% of the demand in North America, Western Europe, and the Far East. Currently, the world demand is around 20,000 tons and is expected to increase 7-8% per year in the next years [6]. Carbon fibers are used in all types of vehicles: aeroplanes, cars, ships, bicycles and more. Carbon fibers have also been used extensively for the production of recreational products such as: golf clubs, tennis racquets, fishing rods and many more. What is it that makes carbon fibers so appealing? What are its weaknesses? The answers to those questions will be provided in the following section.

2.1 Carbon Fiber

Carbon fibers can be made from many types of precursor materials, but rayon, PAN and pitch have been used when mechanical properties are important [4]. Rayon was used in the first generations of carbon fibers, but due to expensive production methods and high mass losses it isn’t popular today [7].

PAN, or polyacrylonitrile, is the most used precursor material for making carbon fibers [4]. The production of a fibre starts with stretching of the PAN until it becomes a very thin fibre (6-10µm) and at the same time it is oxidized in air at 200-300°C [8]. During the oxidization the fiber becomes black and its material structure changes; hydrogen atoms disappear and oxygen atoms are added. When the core of thick fibers doesn’t oxidize the fibers will become hollow later in the production. Hollow fibers have higher strength to weight ratio. The oxidization process is the key limiting factor in the production, even though the time required has been reduced from hours to minutes [4]. The next step is carbonation, where the fibers are heated up to 1000-3000°C [3], but now in an inert gas. Nitrogen is often used for temperatures up to 2000°C and argon for higher temperatures [4]. The exact temperature depends on the properties required. In general, the stiffness increases with higher temperature.

According to Landis et al [9], volatile materials are released during the heating process resulting in a material that is almost pure carbon, or 92-99%. If the temperature goes over 3000°C then the fibers turn into graphite. Graphite is a soft material and has been used as an dry lubricant or pencil lead. The difference between carbon and graphite fibers lies in how the carbon atoms are connected. In graphite fibers the atoms are arranged in sheets. In each sheet they are connected in hexagonal structure, similar to chicken wire. The bonds between the atoms in each sheet are very strong but, the bonds between adjacent sheets are very weak. The weak bonds will break under stress and the sheets slide past one another. This is what makes graphite a good lubricant. The structure of the atoms in carbon fibers is more complicated. It looks like the sheets have been laid in the direction of the fiber and then crumpled. This results in complicated interaction between the sheets and hence it is more difficult for the them to slide.

After the carbonization process the fibers are surface treated and sized. These two last steps influence how the fibers will perform in a composite. By surface treatment the surface area of the fibers can be increased which results in better bonding [10]. The purpose of sizing is to protect

\footnote{1}{Advanced Materials and Processes Technology Information Analysis Center.} \footnote{2}{The Suppliers of Advanced Composite Materials Association}
<table>
<thead>
<tr>
<th>Property</th>
<th>Steel(^a)</th>
<th>Aluminum(^b)</th>
<th>E-Glass(^c)</th>
<th>Carbon Fibers(^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm(^3)]</td>
<td>7.85</td>
<td>2.6-2.8</td>
<td>2.54-2.6</td>
<td>1.75-1.8</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>276-1882</td>
<td>230-570</td>
<td>3448</td>
<td>3530-6370</td>
</tr>
<tr>
<td>Elongation at Break [%]</td>
<td>10-32</td>
<td>10-25</td>
<td>4.8</td>
<td>0.7-2.1</td>
</tr>
<tr>
<td>CTE [10(^{-6})/K]</td>
<td>11-16</td>
<td>20.4-25.0</td>
<td>5.4</td>
<td>(-1.1) - (-0.38)</td>
</tr>
<tr>
<td>Thermal conductivity [W/m-K]</td>
<td>24-65</td>
<td>237</td>
<td>1.3</td>
<td>10-150</td>
</tr>
<tr>
<td>Specific heat [J/g-(^\circ)C]</td>
<td>0.45-2.1</td>
<td>0.9-0.96</td>
<td>0.81</td>
<td>0.71-0.75</td>
</tr>
<tr>
<td>Melting point [(^\circ)C]</td>
<td>1500</td>
<td>477-660</td>
<td>1725</td>
<td>3650</td>
</tr>
<tr>
<td>Resistance [ohm-cm]</td>
<td>1.74\times10(^{-5})</td>
<td>5.2\times10(^{-6})</td>
<td>4\times10(^{12})</td>
<td>0.9-1.6\times10(^{-3})</td>
</tr>
</tbody>
</table>

\(^a\)Carbon Steel, www.efunda.com & www.weldtechnology.com
\(^b\)www.matweb.com
\(^c\)www.matls.com
\(^d\)www.toray.com & www.goodfellow.com

Table 1: Comparison of carbon fiber properties with its rival materials.

them from corrosion, handling and to also improve the resin bonding [11, 3]. If too strong bonding is achieved then the impact resistance of the composite will decrease [12].

The production of carbon fibers using pitch precursor is much less than using PAN. The pitch can be either isotropic or liquid crystalline [3]. The oxidation, carbonization and surface treatment of pitch based fibers is analogous to PAN based fibers [13]. The main advantage that pitch based fibers have over their PAN based counterparts is that the precursor material is cheaper [4]. The fibers have lower tensile and compressive strength. These properties can be improved, but it is expensive [4].

As was mentioned previously, the demand for carbon fibers has increased during the last decades. The main reason for this increase is because of their material properties. Table 1 compares the material properties of carbon fibers with their rival materials. As the table shows, carbon fibers possess some desirable properties, and are well suited for applications where strength, stiffness, weight and damping are important. Carbon fibers are a good choice when corrosion and heat resistance is required. Finally, when strength to weight ratio is important then carbon fiber composites are an excellent choice.

When used in composites, carbon fibers are used as an reinforcement material. The composite will have more strength than the matrix (cured resin) and the fibers have independently. Carbon fibers have been used to reinforce various materials, e.g. cement, aluminium, PEEK (PolyEtherEtherKetone) and epoxy. The discussion will be limited to carbon/epoxy laminated composites. The function of the epoxy matrix is to distribute stress between the fibers [14]. The material properties of an epoxy resin are vastly different from the fibers, e.g. the CTE of an RS-1 epoxy from YLA Inc. is 32 \times 10\(^{-6}\)/K and the tensile strength is 80MPa [15].

Laminated composites are constructed by adding thin layers of sheets and resin. The fibers come as chopped strand mats, woven and unidirectional sheets. Chopped strand mats consists of chopped fibers that are evenly distributed and randomly orientated. The fibers are held together with a binder. The strength of the mats is equal in all directions in the plane of the laminate. Woven sheets are formed from interlacing yarns. They are strongest in the direction of the fibers, i.e. two directions. The orientation of all fibers in a unidirectional sheet is in the same direction. Their strength is therefore almost all concentrated in that direction. The mats and sheets are sometimes pre-impregnated with resin before being stored.

The strength of an composite depends on the ratio of fibers versus matrix. The volume fraction of carbon fibers usually lies between 40-60%. Properties of composites usually depend on the direction in which they are measured. This is called anisotropy. Metals are generally isotropic, which means that their strength and other properties are independent of direction. Composites offer therefore more design parameters, which is something that most designers welcome. The three different types of sheets offer many interesting possibilities for a designer. The stacking sequence and orientation of sheets can be used to obtain desired properties. It is possible to design an composite that can be easily bent, but hard to twist and vice versa, depending on the orientation of the fibers. Also, it is possible to design an composite that shows negligible heat expansion
over certain temperature interval. This is because the coefficient of thermal expansion for carbon fibers is negative but positive for epoxy matrix [3, 13]. However, carbon fiber composites and their manufacturing methods are more complicated than for metals. The number of damage types that can occur in composites is also higher, we will next take a look at them.

### 2.2 Faults and Defects

The reasons why damage occurs can be diverse. But, once a damage has occurred it is more likely that further damage will occur. This is because the damage will weaken the composite. The damage of a composite and its components can roughly be attributed to three different stages in their life; during the manufacturing of the fibers, during the construction of the composite and during the in-service life of the composite. In the following, an overview is given of the most common types of damage found in composites. The organization is based on the origin of the damages, i.e. the three different stages of life.

During the production of carbon fibers, the fibers travel at high speed through the machinery and occasionally they rub against it [16]. The sizing that is put on the fibers is intended to protect them from abrasion, but if they get scratched then the sizing gets damaged and the fiber will lose strength. If the sizing fails then the bonding between the fiber and the matrix is more likely to break. Debonding (Figure 1) of the fiber/matrix interfaces will render the matrix unable to distribute stresses to the fiber, which results in reduced stiffness and different damping characteristics of the composite [17]. According to Schwartz [18] matrix cracks that intersect a fiber and entrapped moisture can also cause debonding. During the construction of a laminated composite, it is important to remove wrinkles when new layers are added. Wrinkles (Figure 3) can cause air entrapment and resin buildup [19]. They can therefore weaken the composite and render the design useless. Air entrapment (Figure 2), sometimes called voids, between the fiber layers. Voids can occur because air gets trapped between layers during the lay-up process. According to Schwartz [18] voids and porosity can be caused by volatile entrapment during curing of the resin. Schwartz also remarks that if they are only partially entrapped then blisters are generated. Blisters are generated in the outermost layers. Voids and blisters weaken the composite and they can also induce the formation of other types of damage. Foreign objects that get entrapped between layers weaken the composite (Figure 3). Examples of foreign inclusion are: dust, hair, grease and other impurities. According to Adams and Cawley [19] stresses can develop around foreign inclusions. Those stresses can cause delamination and other damage. This

![Figure 1: Shows matrix cracks, broken fibers, debonding and delamination.](image1)

![Figure 2: Shows when air gets trapped between layers.](image2)
has been used in research in order to manufacture composites with damage [20, 21, 22, 23]. It is important to use suitable resin for the application, because temperature, stress and moisture can cause damage to the matrix [19]. The ability of the matrix to distribute stresses can change during fatigue loading, hence affecting the endurance limit of the composite [17]. Density variations, due to either too little or too much resin, can have serious consequences for the composite. According to Gaylord [24] too little resin results in inadequate bonding between layers and the formation of voids and porosity. Too much resin lowers the volume fraction of fibers and increases the risk of cracks (Figure 1). If the resin cure temperature is too high or the resin cures too fast then crazing can occur [24]. It is characterized by very fine cracks on the surface and in the matrix. Crazing generally occurs where excessive resin or gel coat is located. The orientation of the fibers is one of the composite design parameters. Fiber misalignment can therefore change the design and generate different load distribution than was anticipated by the designer. In some cases this will cause the matrix to take up the load and the composite will break. During the curing of the resin it warms up and its volume reduces due to polymerization shrinkage but the fibers are unaffected. This generates internal stresses between the matrix and the fibers [25]. When the composite cools down, additional stresses are generated because the matrix and the fibers have different coefficient of thermal expansion [25]. The stresses generated are called residual stresses. The residual stresses affect several properties of the composite, e.g. strength, fatigue and chemical resistance. The stresses can be reduced by extending the curing time.

Most composites require some kind of post processing, e.g. drilling and cutting. Those operations can easily cause damage to the composite. The most common reason for damage is due to forces that are applied perpendicular to the direction of the fibers. But, composites have very little strength in that direction [26]. Delamination (Figure 1) is when the bonds between layers break. It is the most common damage in composites [27, 28, 29]. The weakest bonding between layers is where voids and too much resin is located. When in service, the weak bonding between the layers can break, which reduces stiffness and buckling resistance [20]. Therefore, both too much and too little resin increases the risk of delamination. Delamination can also be caused by impacts [30]. Carbon fiber composites are sensitive to low energy impacts. [31]. The impacts can break fibres, cause delamination and generate cracks [32, 20]. Cracks influence the composite’s chemical resistance and strength. Cut or broken fibers weaken the composite. Fiber failure can be attributed to improper handling, imperfections, and both tensile and compressive stresses. Stresses can develop around the location where the fiber breaks. These stresses can cause other fibers to break.

In next section, we will look at nondestructive test methods that can be used to detect the above mentioned damages.

3 Non-Destructive Methods

Many nondestructive testing methods (NDT) exist that can potentially be used for detecting damages in composites. Some of them are cheap and simple, while other are more expensive and complicated. Cost is however, not a very good criterion for selecting an method. The testing method must be selected after considering several factors, e.g. the cost involved, the time required, the access to the composite, and the ability of the method. The cost includes investments in measurement equipment, software and the training of personnel. All NDT methods require trained
personnel for interpreting the test results. They are also required for setting up, calibrating and operating the equipment.

This section starts with an overview of the main NDT methods used for damage detection in carbon fiber composites. Then two NDT methods that are more suitable for use with fatigue testing are reviewed. These methods use Acoustic Emission signals and the electrical properties of composites.

3.1 Overview

Perhaps the simplest nondestructive testing method for composites is coin tapping [33]. This method, which is still used today, involves tapping the composite with a coin, or a metallic object, and listening for changes in the sound. A change indicates that a damage is present. Damages such as delamination and voids can be detected with this method. The accuracy depends on the operator and therefore it is not a very reliable method. Also, testing can be very time consuming since, in order to fully check a composite, the operator must perform an exhaustive search.

Vibration based methods can be used to measure the frequency response of composites. The methods can detect stiffness reduction which is evenly distributed over the composite, such stiffness reduction is likely to pass undetected by other test methods [34]. A change in natural frequencies is an indicator of changed stiffness. In a paper by Hou and Jeronimidis [35] it is stated that little research has been conducted to investigate the influence of delamination on frequency response. According to Zou et al [36] model based techniques are sometimes used in order to improve the method. They also point out that changes in natural frequencies do not always provide enough information to enable identification of damage type. In a paper by Kessler et al [34] it is pointed out locating a damage is difficult from the measured signal. It follows that determining the orientation and the severity is also difficult. They mention that the accuracy of the method depends on the resolution and the frequency band of the sensors together with the number of sensors and their locations. They also bring up an interesting idea; use vibrations from the surrounding to excite the composite and use it to monitor the composite online. Vibration based methods can also be used for real-time monitoring [37].

Visual tests are also simple tests, performed by visually examining the composite. Visual tests have the advantage of not touching the composite and they are easy to execute. However, like the coin tapping, the accuracy of the method depends on the operator. In order to improve the method, dye-penetrant is used. A dye is sprayed on the composite and it gets drawn into the cracks and pores because of surface tension. In some cases cracks close when a load has been removed from the composite and the dye will not enter those cracks. After a certain dwell time, the composite is wiped clean and a developer is applied. The developer, usually a dry white powder, draws out the penetrant from the cracks and pores. Visual inspection is then performed.

Many instruments and methods have been designed in order to make visual tests more reliable and tractable. Such methods are often called optical tests. During the last few years, two methods have received increasing attention. They are Digital Speckle Photography (DSP) and Electronic Speckle Pattern Interferometry (ESPI). Both use charge-coupled devices (CCD) silicon chips for taking images. The main reason for the increasing popularity of these methods is the rapid development of both algorithms and CCD silicon chips. In DSP a pattern is projected on the surface of the composite. An image is taken at the start of the monitoring. It is then subtracted from all subsequent images. This will generate pattern which is used to detect changes [38]. If two cameras are used, looking at the composite from different angles, then displacements in three dimensions are obtained [20]. The ESPI method uses a laser light source for the generation of the pattern. The light is pointed at the composite and the reflection generates a pattern. Both methods use image processing algorithms for analyzing the images. They are relatively cheap, tractable and can produce results in a short period of time. The methods are sensitive to surface displacements, which can be exploited to detect damages in their early stages. The accuracy is limited to the resolution of the CCD silicon chip [39] and the ability of the image processing software. Optical methods use information obtained from the surface of the composite which makes them limited for evaluation. Many serious damages, e.g. delamination due to impact, can occur well below the surface of the composite [30]. According to Komorowski et al [31] cyclic loading, moisture, temperature and viscoelastic effects can reduce impact dents depths up to 45%. This means that
optical methods will in many cases, not be able to detect such damages at their early stages.

**Thermal Infrared testing** involves taking thermal images of a composite, which can provide information about its inner structure. Infrared cameras with focal plane array (FPA) sensors is one method used for capturing the thermal images. The capturing and post processing of images is analogous to DSP and ESPI, except FPA consists of sensitive, semiconducting heat-sensors and the CCD chip is made up of light sensors. This means that the accuracy of the infrared method is limited by the same factors as mentioned above. Also, the methods require a vibration free environment. The advantage is that they are non-contact methods. With good equipment, thermal infrared inspection can detect voids, foreign inclusions, delamination and impact damage in relatively short time [40].

In **ultrasound testing** pulses of high-frequency sound-waves are transmitted into the composite and the time it takes for them to bounce back is measured. The method allows the detection of voids and delamination deep inside the composite [33]. The main technical difficulties associated with the method are the attenuation, scattering and absorption of the signal and also shadowing effect of multiple damage. Those difficulties make it difficult to test specimens which are thick or of a complex shape. According to Hosur et al. [30] the effect of attenuation and scattering can be reduced by using the appropriate probe and adjusting the pulse parameters. But, the method is time consuming [41] and the need for coupling medium such as water or gel is an disadvantage [42]. There are other ways of transmitting the sound into the composites, e.g. roller probes [43] and air-coupled transducers. The problem with air-coupled transducers is the difference how air and the composite transmit sound [42].

With **radiographic methods** delamination, cracks and foreign inclusions can be detected, and also density and thickness variations [43]. Both residual stresses and load induced stresses can be estimated with the method [44]. The resolution of the method lies between 20-200µm [45, 46], depending on what radiographic technique is used, and damages located at depth of tens of millimeters can be detected [46]. The major drawbacks are high cost, strict health regulations [33] and the fact that it only detects damage that is parallel to the beams [43]. Some radiographic techniques use dye penetrant for enhancement. One of the main problems involved with using dye penetrant is when the penetrant does not enter a crack or does not reach the end of it [47].

This means that internal cracks and delamination that do not extend to the surface will not be enhanced. Also, in some cases cracks close when a load is removed and the dye will not enter.

**Eddy Current** based testing methods are sensitive to the volume fraction of fibers, broken fibers [43] and impact damage [48]. Limitations include: limited penetration depth, surface must be accessible, damage parallel to the scan direction are undetectable [49]. Eddy current can be used to estimate damping characteristics of an composite [50]. Zhang and Hartwig [17] recommended that damping characteristics be used, instead of stiffness, for evaluation of damage. They suggested this because their observations indicated that damping was more sensitive than stiffness.

There are many other nondestructive techniques based on the above methods. However, we are interested in realtime evaluation of the fatigue strength of an composite undergoing fatigue testing. Most of the above mentioned methods require that the test be temporarily halted in order to take measurement. Vibration based methods can be used in realtime. However, due to practical reasons, i.e. excitation source is needed and noise resides in the same frequency band as the signal, we consider it unsuitable for fatigue testing of composites. We will now take a detailed look at two NDT methods are believed to be more suitable.

### 3.2 Electrical Properties

Electrical conductivity is an interesting property of carbon fibers. When the fibers are used in composites, the matrix acts as an insulator. However, during the construction of a laminate composite the resin will flow and the fibers can move and touch each other [51]. Since the fibers are serpentine [52] they only touch at contact points (Figure 4). In practical applications perfect insulation between the fibers is not obtained, hence the composites will conduct electricity in all directions [52]. Nevertheless, the electrical resistance is much higher perpendicular to the fibers than along them. Composites are therefore anisotropic conductors. Since the contact points are randomly distributed the conductivity will vary. According to paper by Louis et al. [53] the num-
ber of contact points will increase with the volume fraction of fibers. If the fraction goes below a critical value then perfect insulation between the fibers is obtained, but such composite will have little strength. Schueler et al. [54] measured the anisotropic resistivity of a composite by using the ratio of electrical resistance in the direction of the fibers against the resistance perpendicular to the direction ($\rho$-ratio). Their measurements for unidirectional composites show that the ratio can be as high as 2000. According to a paper by Todoroki et al. [52] the intra-ply and inter-ply resistivity perpendicular to the fibers should differ because more resin is located between layers than fibers in a ply. Their results confirm this. Their measurements showed considerable difference in the intra-ply and inter-ply resistivity perpendicular to the fibers. However, the results presented by Louis et al. [53] for unidirectional composite showed no difference. The electrical circuit of an unidirectional composite can be simplified by representing the individual fibers as resistors in a parallel network. However, because of the random contact points the circuit is much more complicated and this simple model will not work.

During the last years, a considerable amount of research has been conducted on the electrical properties of composites. Abry et al. [55] showed that the electrical resistance, of an unidirectional composite in the direction of the fibers, increases linearly with increasing length. But, the relation is nonlinear when measured perpendicular to the direction. Wang and Chung [56] investigated the idea of using carbon fiber composites for temperature and light sensing. In a paper by Luo and Chung [57] the idea of using carbon fiber composite as a capacitor was investigated. They visualized the possibility of using the body of solar powered vehicles for storing energy, hence saving space. In an article by Deborah D.L. Chung [58] it is mentioned that carbon fiber composites can be used as thermocouples and their sensitivity and linearity is very good. However, what we are interested in is the answer to the following question: Can the electrical properties of carbon fiber composites be used for estimating its condition? Few of the advantages of using the composite itself as a sensor are identified in a paper by Wang and Chung [59] such as: lower cost, whole structure sensing, and no reduction in mechanical properties, which can occur when sensors are embedded between laminates.

The determination of the electrical resistivity of a composite is often conducted by voltage measurements, i.e. a constant current is sent into the composite and the voltage drop is measured. The resistivity is then calculated by using Ohm’s law. Silver paint is often used to get good conductivity between the composite and the probe. The resistivity of the composite changes if fibers break and the temperature changes. According to Abry et al. [60] different coefficients of thermal expansion for the fibers and the matrix will cause the contact points of parallel fibers to change with temperature. Angelidis et al. [61] explain that the contact points also change when the composite is subjected to strain and this change will locally change the path of the current in the composite. Therefore, local change in voltage can sometimes be attributed to different current path. Matrix cracks and delamination can also change the resistance.

It is not enough to calculate the resistance alone. What is needed is a method that can be used both to monitor strain over time and also to estimate damage. In order to be able to monitor strain over time, then the resistance must change in accordance with the change in strain. But, in order to be able to estimate damage, the resistance increase due to damage must be irreversible. The first condition is a requirement that the composite shows a piezoresistive behavior. Carbon fibers alone do not exhibit such behavior, but with certain production methods it can be attained in composites [62]. As we saw in section 2.2 internal stresses, called residual stresses, are generated during curing of the resin. By increasing the temperature, these stresses can be increased. Then, under tensile loading, the resistivity of the composite reduces because the residual stresses reduce. When the tensile load is removed, the residual stresses increase and also the resistivity

**Figure 4:** Shows how fibers touch.
of the composite. A damage will increase the resistivity of the composite, it will still show piezo-
resistive behavior but around higher mean value. This makes realtime monitoring possible.

The results from electrical measurements depend largely on the location of electrodes and post
processing methods. If the electrodes are located at the ends of an unidirectional composite, then
only average damage will be detected. Average damage will also be detected if the electrodes are
all located at the same side of the composite. Because the current takes the easiest path available,
which is most often in the top layers, this arrangement is not good for detecting internal damage.
In order to be able to detect local damage, the approach and the location of the electrodes must
be different.

Schueler et al [54] measured the conductivity of an composite and used it to build a finite ele-
ment model conductivity map. They used Electrical Impedance Tomography (EIT) for measuring
the conductivity. They connected electrodes to the edges of the composite and sent a current into
it through two of them. The voltage was then measured between all adjacent electrodes. This was
repeated for all electrodes and the information was used to map the conductivity. They argue
that for unidirectional composites, it is sufficient to place the electrodes on edges parallel to the
orientation of the fibers. The assumption was made that the conductivity of the composite in the
direction of the fibers was infinite and damage could be represented by adding resistors perpen-
dicular to the orientation of the fibers. This assumption enabled them to model the composite
as a simple resistor network. They state that this approach can locate and estimate the size of a
damage in realtime, however, they point out that for composites with low $\rho$-ratio the electrodes
must be placed at all edges. Todoroki et al. [52] used a finite element model to investigate the
effect of different spacing between electrodes on the ability of locating and determining the size
of a damage. Their results show that for composites with low volume fraction of fibers, large
spacing has no effect on the ability of locating a delamination damage. But, with higher fraction
then the ability decreases with increasing spacing. Independent of volume fraction, the ability of
determining the delamination length decreases with increasing spacing between electrodes.

Abry et al. [60] and Kupke et al. [63] used both AC and DC measurements for the detec-
tion of damage in carbon fiber composites. The research results of Abry and coworkers show
that DC measurements are more suitable for detecting fiber breakage and AC measurements are
more suitable for delamination and crack detection. The findings of Kupke and coworkers for
DC measurements were similar, but they point out that if contact points are also considered then
delamination can be detected and even distinguished from fiber breakage. AC measurements are
based on measuring capacitance. According to Kupke et al. capacitance is the result of high resis-
tivity of the matrix and decreases during loading because the matrix gets thinner. By introducing
capacitance, modeling of the composite electrical circuit gets more complicated. Since the contact
points between fibers are random, then the location of capacitors is also random. The results pre-
sented by Kupke and coworkers show that the capacitance of the composite decreases gradually
with each load cycle. They suggest that this could be used for monitoring damage accumulation.
Ezquerra et al. [64] investigated the effect of frequencies on the electrical conductivity of carbon
fiber composites. Their results show that the conductivity is almost independent of frequency
which they attribute to high anisotropy.

Monitoring of carbon fiber composites using their electrical properties is very interesting, but
further research must be conducted before the method can be considered reliable for condition
monitoring.

### 3.3 Acoustic Emission

When microstructural changes occur in composites, energy is released and transient stress waves
are generated. These stress waves are called called Acoustic Emission (AE) [65] and approxi-
mately 90% of their activity is located on the 10 to 550kHz frequency band [66]. The amplitude
increases as the energy released increases [65]. The stress waves travel through the composite and
when they reach the surface it will vibrate. The AE in composites is often audible [67]. They can
be heard if the energy that is released is high enough [65].

If a load is applied to a composite and damage occurs, then an AE is generated. The formation
of a damage in a composite involves microstructural changes in the material, which will result in
AE. If the load is removed and then reapplied, then no AE should be generated unless the load is
increased. This phenomenon is called Kaiser effect and is valid for most materials. But, another phenomenon also exists for composites; the Felicity effect. The Felicity effect is when an AE is generated at load level which is lower than the previous maximum. Many sources contribute to this effect; the opening and closing of cracks, rubbing of delamination surfaces and rubbing of parts. AE is also generated under loading because of the different material properties of the fibers and the matrix [67]. AE that comes from other sources, e.g. machinery and electricity, are considered to be disturbances or noise.

AE can be measured by measuring the small surface displacements generated by the vibration of the composite. According to a paper by Duesling [68] piezoelectric sensors are most popular. They are either broadband or resonance. The paper also identifies other types of sensors; capacitance, electromagnetic and optical. The last two are non-contact, but electromagnetic sensors are considerably less sensitive than piezoelectric sensors. Optical sensor, e.g. laser, are free of resonance and can be absolutely calibrated by measuring the correct amplitude of the AE [69]. Measurements using piezoelectric sensors are sensitive to how the vibration is transferred to the sensors. The main factors that affect this are; the surface of the composite, sensor pressure against the composite and the coupling medium [70].

In order to conduct good measurements, it is important to understand how stress waves travel through the composite. The different material properties of the fibers and matrix result in anisotropic speed of propagation, i.e. the stress waves travel much faster in the direction of the fibers [68]. According to Prosser and coworkers [71, 72, 73] classical plate theory, higher order Reissner-Mindlin plate theory and laminated plate theory have been used together for investigating the stress wave behavior in composites. The investigations, based on samples that possess the properties of thin plates, have improved the understanding on how stress waves behave in composites. Prosser et al. explain that the waves propagate through the composite in two modes: as lowest order symmetrical and anti-symmetrical Lamb modes. Those two modes are also known as extensional and flexural plate modes, respectively. They also name few of the mode properties; the largest component of the extensional mode is in the plane of the plate and is symmetric about the midplane, but the largest component of the flexural mode is out of the plane and generally contains lower frequencies and slower velocity. In a research conducted by Seale et al. [74] fatigue damage was estimated by using Lamb wave velocity. The idea was to use Lamb wave velocity to estimate the modulus of the composite, hence allowing estimation of the fatigue damage.

The amplitude of the stress waves decreases as they propagate. The main reasons for the attenuation are; geometric spreading, dispersion, internal friction and scattering [75]. Theoretically, geometric dispersion in two dimensions will cause the amplitude to decrease proportionally with one over the square root of the distance. Viscoelastic properties of the composite will result in different velocities for different frequencies. Because of the velocity difference high and low frequency waves will separate as they propagate and the amplitude will decrease. This separation is called dispersion. Flexural mode components are very sensitive to dispersion but extensional mode components are not [76, 73]. Internal friction of the material As mentioned above, the stress waves vibrate the composite. However, not all of their energy can be used for this, part of the energy will be used to overcome internal friction and also to generate sound. Scattering is when the waves change direction. This can be because of changes in material properties, damages, flaws, and structural elements. Composites are inhomogeneous medium which makes all wave behavior predictions very difficult. The attenuation of stress waves has much influence on the measurements. Geometric spreading alone can cause the amplitude to drop by 20 dB during the first few millimeters of propagation [67]. When the waves come across inhomogeneities or reach the surface of the composite, they will reflect and mix with other waves and distort the measured signal. Reflection is a bigger problem for small composites than large ones. In large composites attenuation will help reducing the distortion due to reflection.

If attenuation was nonexistent, then sensors could be placed anywhere on the composite and the waves would propagate to them. The placement of sensors is however very important in order to get good measurements. In order to determine the placement of sensors and calibrating the measuring equipment, the method of breaking pencil leads, a Hsu-Nielsen source, on the surface of the composite is often used. For this procedure a mechanical pencil and Pentel 2H 0.3 mm lead is used. In a paper by Higo and Inaba [70] it is reported that, in the year 1975 when Dr. Hsu suggested this procedure, 0.5 mm lead was used. The reason for changing the thickness is
because the properties of the lead changed. Change in properties will result in different AE signal when they break. In order to produce consistent AE signal a teflon guide collar is sometimes put on the tip of the pencil. Hsu-Nielsen source has also been used for generating AE in research [75, 77, 78, 79, 72]. According to Prosser and coworkers [72] pencil lead breaks can simulate impact damage and delamination AE.

By measuring AE signals we can possibly detect and monitor changes in the composite. Because micro damage generate AE, the method is promising for detecting damages and monitoring them long before they get serious. Furthermore, this information could be used for predicting the service life of the composite which could be used for maximizing the service life without risking failure. However, the data can be hard to interpret [79, 65]. Based on the idea that each AE source emits a characteristic AE, many research projects have been conducted, over the years, to extract useful information from the signal. Four approaches have been predominant; activity-, feature-, frequency-, and modal-analysis.

**Activity analysis** uses changes in AE activities to detect damage. Load is often used for reference. Two ratios are illustrative for this approach; Felicity and Shelby ratio. Felicity ratio is the ratio of the lowest load that generates certain amount of AE activity, during loading, against the highest load in last cycle [80]. The ratio was described by Dr. Timothy Fowler and has been used as a indicator of damage with mixed results [80]. Instead of looking at the loading of an composite the Shelby ratio looks at the unloading. Shelby ratio is therefore analogous to the Felicity ratio. The Shelby ratio is defined as the ratio of the lowest load that generates certain amount of AE activity, during unloading, against the previous maximum load [67]. If the level of AE activity isn’t reached then the ratio is defined to be 1.0. The Shelby ratio, described by Dr. Marvin A. Hamstad, is useful for detecting damage that generate AE from friction. This ratio hasn’t been used much in the literature, but an AE generated from friction can provide important information about the condition of an composite [81]. Some researchers have attempted to filter the AE signal generated by friction from the total signal in order to better detect AE from damage, but this can be difficult [82]. The fact that a damage only emits AE once but friction many times suggests that approaches based on friction will be more robust.

**Feature analysis** works with features extracted from the AE signal. Conventional features are (see Figure 5); amplitude, event, duration, energy, number of peaks above certain threshold and rise time, which is the time from the detection of an event until the highest amplitude is obtained. Many methods have been devised to extract information about the composite using these features, e.g. using cumulative values, plotting features as function of each other, distribution analysis and more. Different and in some cases contradictory results have been published using these features [77, 83, 84, 68]. In papers by Qi [66] and Prosser et al. [72] this was pointed out and Prosser et al. also discovered that the same type of damage can emit AE signals with different
amplitudes. Godin et al. [85] claimed that conventional AE analysis cannot distinguish between different AE sources and suggested that more advanced methods, such as multivariate analysis and classifiers, should be used. Similar comments were made by Tsamtsakis et al. [82]. They suggested that new parameters, like force or displacement, should be added. The location of an AE source by using conventional triangularization is accomplished by using arrival times. However, due to attenuation, anisotropic speed of the waves and dispersion this method is not robust.

**Frequency analysis** looks at the frequencies in the AE signal and associates frequency bands to different sources. Frequency analysis is most often conducted using FFT processing. The results presented by Bochse [86] determined the frequency bands for three types of damage. Frequencies due to matrix cracks were determined to reside in the 100 to 350 kHz band and fiber breakage was given the interval from 350 to 700 kHz. The sources were classified by using the criterion that 70% of the signal power had to lie within either frequency band. If not, then the source was expected to be debonding. Similar results were presented in a paper by de Groot et al. [23]. The frequency spectrum between 50 to 600kHz was analyzed. They determined that matrix cracks emit frequencies between 90 to 180 kHz, fiber pull-out release frequencies between 180 to 240 kHz, debonding produces frequencies between 240 to 310 kHz and fiber breakage gives AE signal with frequencies above 300 kHz. In the recent years there has been increasing interest in using wavelet based methods for analyzing AE signals. They allow a convenient way to isolate the various frequency subbands. Since AE signals are very weak signals the sensors must be sensitive, which means that they are also sensitive to noise. Noise from the environment is generally a stronger signal than AE, hence noise has the potential of being a huge problem. However, noise is generally located at frequencies that are much lower than the AE signals, and therefore noise is not as big a problem as it could be [77].

**Modal analysis** involves looking at the waveforms and their modes of propagation. For this plate wave theory is used. According to Surgeon and Wevers [78] plate wave theory makes it possible to theoretically study the effects of attenuation and dispersion. They also report that several advantages of the method have been identified in the literature; better at detecting, distinguishing and locating AE sources in addition to be better at handling noise. Prosser [73] was able to eliminate noise by analyzing the waveform of different damages. He found out that cracks create mainly extensional mode waves and both delamination and impacts primarily create flexural mode waves. The noise signal he was dealing with was due to grip damage, which was mainly made of flexural mode waves. He was therefore able to distinguish between noise and matrix cracks. By using the Waveform can be used to locate AE source than is possible with conventional triangularization methods. The location was obtained by matching the similar phase point of the AE waveforms [76, 73]. This resulted in extremely accurate source location. Prosser [87] was able to provide a direct measurement that the cracks initiated at the edge. The downside of the modal analysis approach is that the modeling and signal processing methods can become very complex.

Acoustic Emission is a passive method since it only listens for a signal. An active variant can be created by sending an ultrasound pulse into the composite, allowing it to travel through the material, and measuring it using AE techniques. This method is called Acousto-Ultrasonic and combines AE and Ultrasound methods. The main advantage of this method is that instead of waiting for an AE to be generated, data can be generated manually. Changes in the signal are then used to analyze the composite. According to a paper by Floyd and Phillips [88], the method should be able to detect changes in tensile strength and interlaminar shear strength together with detecting voids, porosity and impact damage. Furthermore it should be able to locate where tensile failure will occur. However, the results presented were unfavorable to the method. They tried to explain the disappointing results by naming some possible reasons; the type of matrix (PEEK) could be incompatible with the method and the instrument settings may have been wrong.

4 **Summary and Conclusion**

A review of nondestructive testing methods has been presented and their potentiality for monitoring composites, undergoing fatigue testing, in realtime discussed. Two approaches stand out: methods based on acoustic emission and the electrical properties of composites. The potential of
these two methods is discussed in greater detail.

The main advantage of these methods is that they do not require the test to be temporarily halted in order to take measurements. Research results show that both methods can be used for the detection and discrimination of damage types such as; delamination, matrix cracks and broken fibers. Furthermore, the results also show that damage can be monitored and the composite condition estimated. Due to the many AE sources in composites the interpretation of the signal can be difficult. For this reason, many methods have been devised, and used with varying results, for the analysis and interpretation of AE signals. Due to attenuation and the fact that the same source can emit AE signal with different amplitude, methods based on thresholds are not reliable. Different and in some cases contradictory results show that further research is needed in order to gain better understanding on both measurement techniques and on the behavior of the stress waves in composites. Most research is based on simple composites. Because of this, and also because of inconsistent findings, methods must be tested and their results compared before they are applied to more complex shaped composites.

In the recent years, there has been increasing interest in smart materials. The electrical properties of carbon fiber composites have been investigated with their potential use as a “smart material” in mind. Using electrical properties for estimating the condition of composites is a very interesting option. These properties haven’t been researched as extensively as the AE signal. Because carbon fiber composites with piezoelectric behavior can be manufactured, it would be interesting to investigate whether their stiffness can be controlled with electricity. This could be exploited for many interesting uses, e.g. to reduce or stop vibration in a composite.

Fatigue testing of composites can take very long time, up to several weeks. It is therefore valuable for an engineer, that wants to test a prototype, to be able to predict the remaining fatigue strength of the composite. If the predicted number of cycles-to-failure is unacceptable, the test can be stopped. Considerable time can be saved by this. By shortening the required time, products can be; designed and developed in less time and at a lower cost than previously possible. In this context there are several interesting topics to investigate:

- Can the AE signal generated during the first time loading of a composite, the Characteristic Damage State [67], be used for predicting the fatigue strength?
- Are the first one hundred cycles in a fatigue test sufficient to predict fatigue strength [89]?
- Can AE be used for estimating damping characteristics, which then in turn can be used for predicting fatigue strength?
- Finally, can capacitance be used for predicting the fatigue strength [63]?

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References


RANNIS's website: http://www.rannis.is


