A Review of Structural Health Monitoring Techniques as Applied to Composite Structures

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Abstract
Structural Health Monitoring (SHM) is the process of collecting, interpreting, and analysing data from structures in order to determine its health status and the remaining life span. Composite materials have been extensively use in recent years in several industries with the aim at reducing the total weight of structures while improving their mechanical properties. However, composite materials are prone to develop damage when subjected to low to medium impacts (ie 1 – 10 m/s and 11 – 30 m/s respectively). Hence, the need to use SHM techniques to detect damage at the incipient initiation in composite materials is of high importance. Despite the availability of several SHM methods for the damage identification in composite structures, no single technique has proven suitable for all circumstances.

It must be noted that the amount of techniques available nowadays is too extensive to be comprehensively reviewed in a single paper. Therefore, the focus will be on techniques that can serve as a starting point for studies focusing on damage detection, localisation, assessment and prognosis on certain kinds of structures. Thus, the line of thought behind the search and the structure of this review is a result of objectives beyond the scope of the paper itself. Nevertheless, it was considered that, once the above was understood, an updated synopsis such as this could also be useful for other researchers in the same field.

Keywords: SHM, composite structures, damage identification, failure mechanisms, low impact, techniques.

1 Introduction

Structural health monitoring (SHM) is a process that aims at detecting, locating, and quantifying damage in structures at an early stage in order to avoid unexpected failure. Most SHM methods are based on the identification of deviations from a “normal” or “healthy” condition. Ideally, deviations should be determined at an early stage of damage initiation and corrected by conducting suitable maintenance procedures, thereby improving structural integrity, reliability, availability and the overall life cycle of the structure (Kessler, Spearing, and Soutis, 2002).

Composite materials have gained a wide acceptance in industries such as aerospace, marine, automotive, civil infrastructures, and sports equipment, due to their unique mechanical properties, namely strength and stiffness to weight ratios (Huang, Sheikh, Ng, and Griffith, 2015; Kessler, Spearing, and Soutis, 2002; Montalvão, Ribeiro, and Duarte-Silva, 2011; Montalvão Diogo, Dimitris Karanatsis, António MR Ribeiro, Joana Arina, 2014; Ye Lin, Ye Lu, Zhongqing Su, 2005). Composites result from the combination of two or more different materials in an attempt to form a single material that has enhanced mechanical properties when compared to the individual properties of the constituting parts. In the more particular case of composite laminates, these are comprised of two or more layers that are laid together (Varga, Vretenar, Kotlar, Skakalova, and Kromka, 2014), reinforced with aligned fibres (e.g., carbon) (Notta-Cuvier, Lauro, Bennani, and Balieu, 2014) and a matrix (e.g., epoxy resin) acting as the bonding medium.

However, during maintenance, assembly or use, composite materials may be subjected to low-velocity impacts that can result in barely visible impact damage (BVID) (Montalvão, Ribeiro, and Duarte-Silva, 2011; Shyr and Pan, 2003). This is because of the poor properties in the through-thickness direction of the CFRP (Zhang and Zhang, 2015). Typically, in BVID, the impact on the surface does not result in a mark other than a small indentation that is difficult to identify through visual inspection. However, the impact may have resulted in damage that propagates under different mechanisms through the thickness of the laminate down to the opposite side which is usually hidden (Cantwell and Morton, 1989). This could compromise the integrity of the structure, reduce its life cycle (Abrate, 1994) and raise safety issues. Hence, the need to use SHM to detect damage at its incipient stage of initiation in composite materials still is of high importance. Failure mechanisms in composite materials include matrix cracking, fibre fracture, debonding, fibre pull-out, micro-buckling, and kink band (Alexandrov, Erisov, and Grechnikov, 2016; Sause, Müller, Horoschenkoff, and Horn, 2012). This may happen through a chain of triggers such as excessive loading conditions or even low to medium velocity impacts (Montalvão, Ribeiro, and Duarte-Silva, 2011).

Several techniques such as ultrasound, X-ray, visual inspection, acoustic emission, or eddy-currents, among others, have been used for SHM (Maia, Almeida, Urgueira, and Sampaio, 2011). However, none of these techniques have proven adequate for all applications, because they all have their peculiar advantages and limitations. Nonetheless, having the idea about their applications is vital in structural health monitoring of composite facilities in several industries. Over the years, SHM has evolved and prompted the development of online methods for monitoring. These methods are primarily based on the information collected from smart materials, novelty-based, mechanical properties, image processing, statistical pattern recognition, and optical fibres (Maia, Almeida, Urgueira, and Sampaio, 2011).

This article presents a review of the literature on different types of failure modes and some of the existing techniques for damage detection in composite materials, highlighting their advantages and limitations, with special emphasis on carbon fibre-reinforced plastics (CFRPs). Therefore, this paper offers some updated guidelines for the users of composites on some of the recent advances in SHM applied to composite structures; also, most of the studies reported in the literature seem to have concentrated on the flat composite plates and reinforced with synthetic fibre. There are relatively fewer stories on other structural configurations such as single or double curve structures and hybrid composites reinforced with natural and synthetic fibres as regards SHM.

2 Failure Mechanisms of Composite Materials

Due to the high strength-to-weight and stiffness-to-weight ratios of CFRP composites, these materials have been widely applied in the aerospace, civil, marine, transport, and oil industries. However, their complex damage (Schwab, Todt, Wolfahrt, and Pettermann, 2016) and failure morphologies such as intralaminar and interlaminar failures (Liu, Chu, Liu, and Zheng, 2012) constitute a hindrance on their application. Typical failure mechanisms that will be discussed in this section include matrix cracking, fibre fracture, debonding, fibre pullout, delamination, micro-buckling, and kink bands.

2.1 Matrix Cracking

Matrix cracking is the first type of damage that occurs in composite laminates (Nairn and Hu, 1994). This is characterised by cracks that develop between two or more layers that are parallel to the fibres in the ply and extend through the thickness of the ply (Nairn, 2000). According to (Gayathri, Umesh, and Ganguli, 2010; Hu, Liu, Li, Peng, and Yan, 2010; Jen and Lee, 1998; Tong, Guild, Ogin, and Smith, 1997), matrix cracking in carbon fibre/epoxy (CF/EP) laminates occurs across the whole cross sectional area of the perpendicular plies. This may or may not trigger other failure modes, depending on the stresses generated due to temperature variations, quasi-static loads or impacts.

Matrix cracking alone does not usually constitute a problem to structural integrity. However, since it is the forerunner of other (more serious) failure modes in composite laminates, it has deserved much attention from researchers. For example, extensive research has been conducted by (Gayathri, Umesh, and Ganguli, 2010; Henaff-Gardin, Lafarie-Frenot, and Gamby, 1996; Nairn, 1992; Park and McManus, 1996) on matrix cracking and its impact on the performance of composites. However, cracks due to the manufacturing process of composite laminates were not considered.

2.2 Fibre Fracture

Common sense would say that fibre fracture reduces both the stiffness (Young's modulus) and the strength of the composite. For example, the impact of the fibre fracture on the stiffness of the composite laminate was studied in (Craven, Pindoria, and Olsson, 2009). It was observed that the initiation of the fracture mechanism in the composite has more effect on the buckling load than the reduction of its stiffness. Also, the result shows that fibre fractures have little effect on the stiffness of the composite when compared to its effect on the strength of the material. Therefore, the load carrying capacity of a laminate should be investigated as soon as the fracture is observed.

A novel method was presented by (Davidson and Waas, 2012) to study the fracture of fibre-reinforced composites. Their study focused on the mode I fracture (opening) of carbon fibre and glass fibre unidirectional composites under quasi-static loading. Their result indicates that crack progression shows smooth and discontinuous responses. The researchers used a simple algorithm based on the critical fracture internal stress or strain, and a critical material specific crack velocity was used to validate the experimental results; but the crack initiation toughness was not feasible due to loading rates of the quasi-static testing.

Some researchers, (Bedsole, Bogert, and Tippur, 2015) introduced carbon nanotubes into the interlaminar zone of unidirectional CFRP composite in order to enhance the properties of interlaminar and intralaminar fracture under dynamic and quasi-static loading conditions. They studied the dynamic interlaminar crack initiation and propagation in a fibre-reinforced composite material under dynamic loading using a digital image correlation. Although their results showed that carbon nanotubes improved the fracture toughness of the material when under dynamic and quasi-static loading conditions, they did not improve the critical stress intensity factor.

Furthermore, Vaughan and McCarthy (2011) presented a Micromechanics damage model to study the impact of intra-ply properties on the transverse shear deformation of a CF/EP composite. Their study assumed that the parameters describing Mode I and Mode II failures are the same. They observed that the thermal residual stress has a high influence on the initial damage location in the microstructure, but has less influence on the overall shear response. It was also found that due to the thermal residual stresses, the transverse fracture surface contracted slightly under the combination of transverse normal and shear loading. However, more research is needed to study how the mixed-mode behaviour of the interface crack progression for strength and fracture energy.

2.3 Debonding

Debonding normally occurs in areas with high interfacial stress concentration (Neto, Alfaiate, and Vinagre, 2016), which are related to the presence of cracks. When subjected to an impact load, a large part of the fibre may be pulled off when adhesion fails. Several factors such as differential thermal stress, crack, ageing structure (Dhieb, Buijnsters, Elleuch, and Celis, 2016; Swamy and Mukhopadhyaya, 1999), low-velocity impact, environment and poor design could be responsible for such phenomenon to occur. Although debonding is not the primary cause of failure in composite materials, it compromises the strength at its location and the surrounding fibres, which may result in a breakdown when overloaded (Gamstedt, 2000).

2.4 Delamination

Delamination in fibre composites is mainly caused by impacts from foreign objects. It is one of the most vital failure modes in composite materials because of the strength of the composite laminates is inversely proportional to delamination (Latifi, Van der Meer, and Sluys, 2015). That is, as the rate of delamination increases, the cohesion between the plies of the composite reduces. Hence, it is necessary to understand if delamination has initiated.

A penalty-based method was used by Barbieri, and Meo (2009) to modelled delamination in composite structures. Although the simulation and the experimental results agreed; only single mode delamination was considered. It would make sense to consider the multiple mode delamination under mode I and II quasi-static loading with a proposed approach to test its robustness. Schön (2000) developed a model to determine the fatigue delamination growth rate in a composite laminate. The model needs to experimentally determining the critical static energy release rates, delamination growth rate at which the critical energy release rate for quasi-static loading is reached, the delamination growth rate, and the threshold value of energy release rate of the delamination crack during a fatigue cycle.

Also, Argüelles, Viña, Canteli, and Bonhomme (2010) evaluated crack initiation and propagation, which influence the delamination process under modes I and II fatigue loading in the composite material. It was concluded that the accumulation of resin and the manufacturing procedure of the composite laminate have a high impact on the fatigue curves of delaminated specimens. However, the researchers did not consider the effect of temperature increase on the rate of crack growth, which could have been of help in determining the remaining useful life of the structure.

2.5 Fibre Pullout

Weak bonding within the laminates is the major cause of fibre pullout. Hence, (Pochiraju, Lau, and Wang, 1995) studied the stresses caused by fibre pullout when fibre matrix experienced frictional sliding and underwent compressive thermal residual stresses. They applied asymptotic analysis and Muskhelishvili-Kolosov theory to solve the stress within the area where the fibre was pulled out. A fibre pullout test is therefore required to determine the thermal, mechanical properties (stiffness and strength) of the interfaces in a CFRP (Chandra, and Ghonem, 2001). Two methods are used to conduct fibre pullout tests, namely single pullout test and multiple pullout tests. Although single fibre pullout test is easier to apply, it is not suitable for fibres with small diameters (Yue, and Padmanabhan, 1999). The multiple fibre pullout test method uses a large part of fibres, and it gives the comparable results to the single fibre pullout test.

Furthermore, Yue, C. Y., and Padmanabhan (Yue, and Padmanabhan, 1999) used the multiple fibre pullout test technique to determine the possibility of increasing the interfacial strength of Kevlar fibre/epoxy composites. Obviously, the multiple pullout tests gives a better result than the single pullout test. In addition, Jia, Chen, and Yan (2014) proposed a numerical method to probe the fibre pullout in a Carbon nanotube (CNT)–hybridised carbon fibre (CF). The result shows that the added bonding of the CNT matrix interface can increase the specific pullout energy and the interfacial shear strength of the hybrid fibre.

2.6 Micro-buckling

Fibre micro-buckling reduces the compressive strength of CFRPs (Harich, Lapusta, and Wagner, 2009; Lee, and Soutis, 2007; Vinet, and Gamby, 2008). It affects the mechanical properties and the matrix of the composite laminates. The local failure and matrix crack occur due to micro-buckling (Zheng, and Engblom, 2002). Several researchers have conducted an experiment on the cause and effect of micro-buckling in composites. Also, Berbinau, Soutis, and Guz (1999) examined the shear strains that developed in the matrix as a result of fibre micro-buckling. It was confirmed that fibre failure starts on the compression side of a composite, where the maximum fibre curvature occurs. However, they did not study the impact of fibre/matrix boundary on the formation of fibre microbuckling.

Also, Mohammadabadi, Daneshmehr, and Homayounfard (2015) studied the thermal buckling of micro-composite laminates and the impact of shear deformation in the composite laminate based on modified couple stress theory and using Reddy beam, Timoshenko beam and Euler-Bernoulli beam theories. Except cross-ply laminates, the researchers did not investigate quasi-isotropic, orthotropic, anti-ply, anti-symmetric and balanced laminates. Maybe investigating other laminate configuration would offer a more reliable result. In addition, Huang, Sheikh, Ng, and Griffith, (2015) proposed the use of finite element analysis (FEA) to study micro-buckling in grid stiffened composite plates with different grid configurations. They studied the buckling load capacity of different grid-stiffened composite laminates, such as x-grid, ortho-grid, iso-grid, and bi-grid. Although based on their results, the proposed modelling suitable for stiffened plates, there was no attempt on applying it on stiffened curved structures. Hence, more research on grid stiffened curved structures would be necessary.

2.7 Kink Bands

A kink band is a deformation that has a pronounced twist of the fibres with a deviated orientation from the original orientation on the composite laminate. It occurs due to fibre dislocation or plastic micro-buckling in the composite laminate (Wind, Steffensen, and Jensen, 2014), which is caused by compressive forces. Kink bands reduce the compressive strength of a composite laminate. When formed it expands continuously at a constant stress level known as propagation stress (Vogler and Kyriakides, 1999). Three researchers, Budiansky, Fleck, and Amazigo (1998) examined the transverse and band broadening kink propagation based on the nonlinear couple stress theory of composite kinking in one dimension. Their aim was to study the effect of fibre bending resistance, the mechanics of kink band broadening and transverse propagation. See more information on their work in (Budiansky, Fleck, and Amazigo, 1998). The researchers considered the kink angle as a prescribed quantity, but did not state how the angle should be selected. Also, they only considered kinking in 1-D and no attempt was made on 3-D. The authors has not been able to identify earlier works on kinking in 3-D. Recently, Svensson, Alfredsson, Stigh, and Jansson (2016) developed a model to estimate the cohesive law related to kink band's evolution in a unidirectional composite laminate. They modelled the formation of a kink band in a unidirectional CF composite using a cohesive zone model. Their results revealed that kink band is developed with a height of nearly 200μm. However, Svensson, Alfredsson, Stigh, and Jansson (2016) only analysed a unidirectional CF composite, but considering a multidimensional CF composite material would be encouraged.

Despite the immense studies conducted by several researchers to find how compressive failures occur, it has not been easy to estimate the compressive failure in a unidirectional composite. An increase in compressive load introduces fibre damage in the composite. Kink bands could be triggered by the transverse movement of fibres that are close to broken fibres due to shear failures at various frail defects (Bai, and Phoenix, 2005). The initiation of kink bands on a composite laminate drastically reduces its strength and causes it to fail. This was analysed experimentally and through analytical models by Bazant, Kim, Daniel, Becq-Giraudon, and Zi, (1999). It was confirmed that the size of the kink band has a noticeable effect on its propagation. In addition, Vogler, and Kyriakides (1997) experimentally analysed APC-2/AS4 thermoplastic composites and observed that the quasi-static propagation of kink bands occur in a stress point as high as 40% of the toughness of the undamaged material. The propagation stress is not sensitive to minute irregularities in fibre, and may not be a concern in design consideration.

More also, Gonzalez-Chi, Flores-Johnson, Carrillo-Baeza, and Young, (2010) measured the distribution of axial stress around a kink band on a fibre installed in a thermoplastic model composite using Raman spectroscopy (it reveals the structure of a material) technique. They found out that the maximum interfacial stress was close to the kink band where the bond between the fibre laminate is still intact. However, further research is needed at higher levels of strain in composite to ensure more debonding that is far from the location of kink band. Also, (Hsu, Vogler, and Kyriakides (1999) simulated the steady state, broadening of kink bands with a micromechanical model as examined by Vogler and Kyriakides (1999). The model could forecast the propagation, stress remarkably. Nevertheless, using a realistic representation of the manner deformation in the kink band, would improve the quantitative accuracy. Likewise, Pimenta, Gutkin, Pinho, and Robinson (2009b) developed a micromechanical model for the formation of kink bands in a unidirectional fibre reinforced composite. This study followed the one from Pimenta, Gutkin, Pinho, and Robinson (2009a). The model could predict the width of the kink band, the deviation and primary stress fields in fibres and matrix at various phases of the formation of the kink band, the longitudinal compressive toughness of the composite, and the direction of the fibres when the failure was initiated in the fibre.

Furthermore, Pimenta, Gutkin, Pinho, and Robinson (2009a) investigated the inception and the propagation of kink bands using numerical models and experimental examination. The results show that the formation of kink bands is related to the weakening of the matrix, whereby the fibres around the compressive area fail before any other location. The rate at which kink band releases energy in a unit load decreases initially, but increases at a certain length of propagation (Zi, and Bažant, 2003).

3 An Overview of Damage Identification in Composite Materials

Many techniques have been developed over the years to detect damage at an early stage in composite materials. However, it is not possible to have a single technique that can be effective for all loading conditions, material constitution and failure modes. All techniques have their own advantages and limitations. The application of a technique can be based on the criticality of the equipment, available resources, and skilled personnel to apply it.
The aim is to increase the reliability and availability of equipment with the available damage detection technique at the lowest cost without compromising standards. In this section, a critical review of some of the damage identification techniques is presented.

3.1 Vibration-based

Most vibration-based methods are based on the relationship between the change in the state of the structure and the change in its vibration response. That is, the change in the dynamic properties of the structure may be related to the presence of damage. For instance, the presence of damage in a structure may alter properties such as the stiffness and strength. Since dynamic models may be described from the structural properties of mass, stiffness, and damping, then it is plausible to presume that the vibration responses of the structure at an undamaged state will differ from the damaged state. Hence, it is often necessary to have a prior knowledge of the vibration responses of the undamaged structure to use as a set standard. Vibration-based structural health monitoring for damage detection is time saving and relatively cost-effective. It can also be applied in real-time monitoring of structures.

According to, Maia and Silva (1997), in dynamics, the properties of a system with an N-degree of freedom (DOF) can be illustrated with either spatial, modal or response model – that can be linked to each other by either forward or inverse paths (Montalvão, 2010).
The dynamic characteristics are contained in a spatial distribution of mass, stiffness, and damping properties represented in terms of matrixes of mass $[M]$, stiffness $[K]$, and damping $[C]$ (for a viscously damped model) or $[D]$ (for an hysterically damped model) (Diogo Montalvão, 2010). Let each DOF be expressed by a coordinate $x_i(t)$ with an applied force $f_i(t)$ where $i = 1, 2, 3, \dots, N$ DOFs, then the model can be illustrated using the Newton's second law of motion:

$$[M]\{\ddot{x}(t)\} + [K]\{x(t)\} + i[D]\{x(t)\} = \{f(t)\} \quad (1)$$

if the case is a hysterically damped model, or:

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = \{f(t)\} \quad (2)$$

if the case is about the viscously damped model. It is quite difficult to deal with the viscously damped model illustrated in Eq. (2), where damping is non-proportional (Maia and Silva, 1997). It is worthy to note that, in real cases viscous or hysteretic damping is non-proportional. However, to solve the equations, it is often useful to consider the approximation that it is proportional, as it eliminates coupling and we get a diagonal matrix. Hence, proportional damping can be assumed as a special case of damping and it suggests that the damping matrix is a linear combination of the mass and stiffness matrices. In the case of the hysteretic damping, this is:

$$D = a[M] + b[K] \quad (3)$$

where a and b are real scalars. This kind of damping model is also known as classical damping or Rayleigh damping. The dynamic behaviour of structures that are subjected to varying loading is usually illustrated by constant hysterical damping model. Hence, the equation of motion will be based on the hysteretic damping. Assuming there is a general solution of the form:

$$\{x(t)\} = \{\bar{X}\}e^{i\lambda t} \tag{4}$$

where $\{\bar{X}\}$ is an $N \times 1$ vector of time-dependent response amplitudes, and substituting it into Eq.(1), we will have:

$$\left[[K] - \lambda^2[M] + i[D]\right]\{\bar{X}\} = \{0\} \tag{5}$$

which is a complex eigenvalue problem, when solved results in the solution described by N complex eigenvalues λ_r^2 and N real eigenvectors Φ. The λ_r^2 have information on the natural frequencies of the system and Φ has information on the mode shapes. The complex eigenvalue λ_r^2 can be defined as:

$$\lambda_r^2 = \omega_r^2(1 + i\eta_r) \tag{6}$$

where $\eta_r$and ω_r are the damping loss factor and natural frequency, respectively, for mode r. The spatial model can be linked with the modal model by orthogonality conditions of the modal matrix:

$$[\Phi]^T[M][\Phi] = [\mathrm{I}] \tag{7}$$

$$[\Phi]^T[K] + i[D][\Phi] = [`\lambda_r^2`] \tag{8}$$

where $[\mathrm{I}]$ is the identity matrix, $[\Phi]$ is the mass-normalised mode shape matrix. This also means that the mode shape matrix is a non-singular invertible matrix (Montalvão, 2010). Hence, a spatial description of the model can be obtained from the modal model and conversely.

However, instead of that, a response model described by Frequency Response Functions (FRFs) is obtained. Considering the frequency domain in a steady state, the FRF $H(\omega)$ can be determined for each frequencyω:

$$H(\omega) = \frac{X(\omega)}{F(\omega)} \tag{9}$$

where $X(\omega)$ is the complex response and $F(\omega)$ the complex force. The FRF is also called *receptance, mobility, or accelerance,* depending on the complex response being defined as displacement, velocity, or acceleration, respectively. These quantities can be related with each other by differentiation and integration. According to, Maia and Silva (1997) and in the case of a receptance, the relationship between the response model and the modal model is:

$$[\alpha(\omega)] = [\Phi][`\lambda_r^2 - \omega^2`]^{-1}[\Phi]^T \tag{10}$$

where $[\alpha(\omega)]$ is the receptance matrix. Hence, starting with a spatial model a response model was obtained after going through an intermediate modal model. This sequence is normally performed when the starting point is a theoretical analysis. Nonetheless, if the complexity of systems is such that it is difficult to model it analytically, the inverse method should be followed where the starting point is the response model with the experimental measurement of the system FRFs. Several methods allow derivation of the experimentally obtained response model of the modal characteristics of a given system (Maia and Silva, 1997). The procedure is known as modal identification. Fig.3.1 shows the relationship between spatial, modal, and response models.

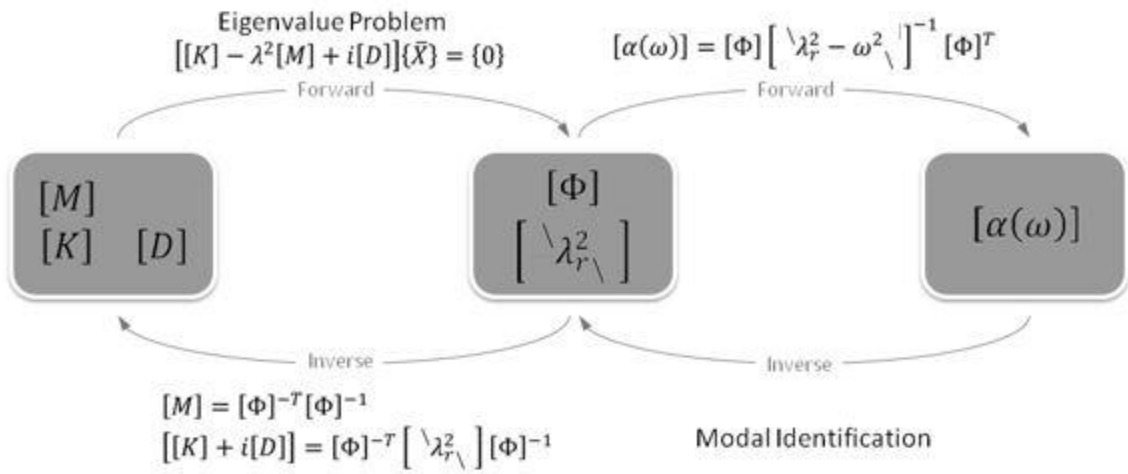

Figure 3.1 Dynamic models interrelation (hysterical damping case) (Diogo Montalvão, 2010)

Each term of the receptance matrix in Eq. (10) would be of the form:

$$\alpha_{jk}(\omega) = \frac{\overline{X_J}}{F_k} = \sum_{r=1}^{N} \frac{{}_r\bar{A}_{jk}}{\omega_r^2-\omega^2+i\eta_r\omega_r^2} \qquad (11)$$

where $\overline{X_J}$ is the complex response amplitude in the j coordinate and F_k is the amplitude of the applied force in the k coordinate.

3.1.1 Modal Strain Energy

Ooijevaar, Loendersloot, Warnet, de Boer, and Akkerman (2010), investigated a vibration based damage identification method known as the modal strain energy damage index algorithm, by applying it to composite T-beams that are vibrating under bending and torsional modes, to detect and localise delamination. A Laser Doppler Vibrometer (LDV) was used to determine the FRFs between the point of excitation and the measurement points along the test specimen. The authors obtained the modal parameters (modal damping factors, natural frequencies, and mode shapes) from the FRF measurements using Experimental Modal Analysis (EMA). The results show that the measurement of changes in the natural frequencies of the bending modes can be used to detect damage in the specimen.

However, the sensitivity of the damage index depends on the distance between the delamination and the measuring points. They affirm that as the number of measurement points reduces, the sensitivity of the damage index to detect damage at some distance from the measurement points is affected. Although the frequency response measurement method can be used to detect relatively small damage in a simple structure, it cannot be generally used on its own to provide information about the type, size, location, and orientation of damage (Kessler, Spearing, Atalla, Cesnik, and Soutis, 2002).

3.1.2 Frequency Method

Kim (2003), identified damage in both laminated composites and sandwich composite beams using the reconstructed residual FRF-based damage identification method. The method is based on the differences between the FRFs of damaged and undamaged test structures. It was found that the changes in the natural frequencies and modal damping ratios of a composite structure can be used to identify debonding or delamination because the FRFs are noticeably affected by the global changes in stiffness and damping due to the delamination in the composite structure (Kim, 2003). However, the damage indicator based on the measured FRF-curve area is not consistent. The FRF-curve area is the potential energy density of the structures based on the assumption of unit inertial energy density (Kim, 2003).

Manoach, Samborski, Mitura, and Warminski (2012) investigated nonlinear vibration models to study the impact of damage on the vibration response of structures with varying temperatures. The damage detection method was based on Poincaré maps of responses, which is a standard tool used for dynamic system inspection (Manoach, Samborski, Mitura, and Warminski, 2012). The authors confirmed from their results that damage can affect the time domain response of a beam and that a change in temperature leads to a nonlinear change in the dynamic response of the beam. A useful aspect of this method is that the prior knowledge of a reference healthy state of the structure is not needed. However, the proposed method by the researchers was not applied on CF composite, but only glass-epoxy composite.

Herman, Orifici, and Mouritz (2013) used wavelets (Sung, Kim, and Hong, 2002) to detect damage in composite T-stiffened panels, which are often used in the aviation industry and other light structures. A scanning LDV was used to measure the displacements and mode shapes induced by elastic stress waves at different frequencies (Herman, Orifici, and Mouritz, 2013). They followed a typical approach whereby any deviation in the modal properties between the undamaged and damaged states is used to detect and localise damage. Both numerical and experimental analysis was conducted and correlations between the modal parameters and the presence of damage, either in the form of cracks or porosity was seen. However, damage identification in regions with high damping properties was not possible with their method.

Pérez, Gil, and Oller (2014) studied the possibility by using vibration-based techniques to detect low impact damage in composite laminates. The authors assessed and compared four modal-based damage indicators (frequency shift, mode shape change, curvature mode shape change and residual load-bearing capacity) by comparing results from undamaged and damaged states. Additionally, their study investigated the effectiveness of the damage indicators in detecting damage, its location, and the damage progression in the test specimen. They found that relative changes in the natural frequencies are smaller than those seen for mode shapes. However, they also noted that the sensitivity of the damage indicators depends on the number of measured coordinates (DOFs) and the number of modes within the measurement frequency range. Based on these limitations, further research would be needed to study a large structure with the proposed method.

Wang, Qiao, and Xu (2015) conducted numerical analysis of anisotropic composite laminate plates and examined the impact damage had on the vibration characteristics. The damage was modelled as a local reduction of the stiffness. The severity of damage, damage anisotropy (the ratio of the reduction of stiffness in each direction to the reduction of stiffness in the longitudinal direction) and damage location, were the damage features used to describe different damage scenarios in the composite structure (Wang, Qiao, and Xu, 2015). The dynamic governing equation was proved based on classical theory and the perturbation method was used to obtain the analytical solutions. An FEA was conducted to verify the effectiveness of their proposed method. The results show that the impact of the vibration characteristics of the three damage features is not similar. Unlike the modal curvature and strain energy, the natural frequencies and modal displacements are less sensitive to damage. The numerical results show that: damage in the longitudinal direction has the highest impact on the vibration response when compared to other directions. The damage has more impact on the vibration characteristics when it is away from nodal lines and an increase in the severity and size of damage results in a reduction in the natural frequencies and modal strain energy. Wang, Qiao, and Xu (2015) suggested that the perturbation-based vibration analysis developed can be used to assess the impact of damage on the vibration characteristics of anisotropic plates and also detect damage in laminated plates.

Many other vibration-based methods use aspects of the vibration response. Since these are very broad, it was decided to further discuss them in different independent sections, as is the case of Transmissibility based methods.

3.1.3 Transmissibility

Transmissibility analysis has gained a lot of attention in the past decade due to its simplicity of implementation, as it uses conventional vibration transducers and does not require that the loading conditions are known. In simple terms, the ratio between two measured outputs (responses at different coordinates) is known as the transmissibility function (TF) (Devriendt, Presezniak, De Sitter, Vanbrabant, De Troyer, Vanlanduit, and Guillaume, 2010),(Mao and Todd, 2012). Among other types of frequency domain system identification methods, some authors argue that the transmissibility response methods are more sensitive to local variations in the structure: it is suitable for output-only data from the structure and it is sensitive to local structural changes (Mao and Todd, 2012; Zhou, Perera, and Sevillano, 2012). In other words, transmissibility does not consider the excitation force (input data); rather it uses only responses (output data). Therefore, since it does not require the loads to be known, it can be considered as a case of the broader area of operational modal analysis (OMA), tackling at least one issue from EMA. Among the first to explore the concept of Transmissibility in Multiple Degree-of-Freedom (MDOF) systems is (Ribeiro, Maia, and Silva, 2000; Ribeiro, Silva, and Maia, 2000; Ribeiro, Maia, and Silva, 1999).

In order to reduce or eliminate human error and cost during data collection from structures, (Yi, Zhu, Wang, Guo, and Lee (2010) developed mobile sensors to detect damage in civil structure and transmit it to a computer for processing. They used transmissibility function analysis to process the data extracted from the structure by the mobile sensors, to detect damage in the structure. The proposed technique can locate damage under certain circumstances. Furthermore, few sensors are needed and it does not need extensive human effort to work. However, the authors agreed that more study is needed to enable the mobile sensors to detect a wider range of other potential damages in the structure.

Lang, Park, Farrar, Todd, Mao, Zhao, and Worden (2011) exploited the impressive properties of NOFRF transmissibility to develop an approach that can identify and locate not just linear, but also non-linear damage in structural systems with multidegree of freedom. The concept of NOFRF was proposed to analyse nonlinear systems in the frequency domain (Lang and Billings, 2005). They defined the concept of transmissibility of the NOFRFs as the ratio of the maximum order NOFRFs linked with two varying output responses of concern in a nonlinear system. The NOFRF transmissibility depends only on the linear characteristics of the system; hence does not change with the system's inputs. The researchers conducted both experimental and numerical studies to confirm the technique. Their results show that the technique is effective and it can be used for both detection and localisation of damage in real structures. Although the effectiveness of the new technique is not in doubt, but only a simple MDOF structural system was analysed. Hence, it would be unfair to make a generalised conclusion, until a complex MDOF systems model is considered.

According to Devriendt and Guillaume (2007), it was not always feasible to use transmissibility measurements to identify modal parameters. However, since the transmissibility changes with the location of the input forces, it can be used to determine the system's poles Devriendt and Guillaume, (2007). The authors could identify the modal parameters of a structure by combining transmissibility measurements under various loading conditions. The loading conditions were achieved by a change in ambient forces or by using an impact hammer to apply forces at different locations on the test specimens Devriendt and Guillaume (2007). Unlike the classical output-only techniques, the transmissibility-based method does not require the operational forces be white noise; it can be a swept sine, coloured noise, impact, etc. (Devriendt and Guillaume, 2007, 2008). Similarly, Devriendt, Presezniak, De Sitter, Vanbrabant, De Troyer, Vanlanduit, and Guillaume (2010) detected and located damage frequency domain TFs. They suggested the use of small frequency bands only that are close to the resonance frequencies of the structure to detect damage. In addition, the required frequency band should be selected to improve the reliability of the method. Both numerical and experimental results were presented to confirm the technique in damage detection. However, the application of this technique needs highly skilled personnel.

Sampaio, Maia, Ribeiro, and Silva (2001) summarised the concept of transmissibility and used it to detect and localise damage in structures. In their work, the special case of the transmissibility matrix for an MDOF is defined as:

$$\{X\} = [T]\{X\} \tag{12}$$

where $[T]$ is the transmissibility matrix as a function of the frequency that relates itself with all the set of measured responses contained in the response vector $\{X\}$. It is like *auto-transmissibility* (Sampaio, Maia, Ribeiro, and Silva, 2001). The presence of damage in the structure would show variation in $[T]$, and it will become T^d. The d stands for damage. Their work was focused on damage detection and localisation. The authors presented a graphical display of the undamaged $[T]$and damaged T^d for each frequency to make it possible to visually detect any deviation in the transmissibility coefficients that revealed the presence of damage in the structure. According to Sampaio, Maia, Ribeiro, and Silva (2001), the global matrices for the healthy and damaged cases can also be obtained by summing up all the frequency range. From their results, it is shown that the method they presented has the potential for both damage detection and localisation. They assert that, although the damage location can be revealed by summing up the changes between the transmissibility maps for all the frequencies, the wide difference that can ensue near the resonances and anti-resonances will affect the process. However, the limitation was prevented by counting how many times the differences in the maximum transmissibility occur in each structural element.

Maia, Almeida, Urgueira, and Sampaio (2011) proposed the use of the transmissibility response function measured along the structure to detect and quantify the severity of damage. They conducted some numerical simulations and compared the results with those obtained from frequency response functions (FRFs). The authors also confirmed the proposed method by experimental testing. It was confirmed that the transmissibility is sensitive for the detection and quantification of the damage extension. They compared the results of the DRQ and the transmissibility damage indicator (TDI) from numerical and experimental results. The two indicators are based on the RVAC correlation factor. It was seen that the TDI detects and quantify damage better than the DRQ. In addition, the more the measured coordinates for each applied force, the better the results achieved with TDI. However, the effectiveness of the method depends on the number of measurement points, for a given number of forces applied.

Devriendt and Guillaume (2008) conducted a numerical experiment on a cantilever beam and compared the results from input-output modal analysis based on frequency response functions (FRFs) and output-only responses based on transmissibility measurements. It was seen that the correct system poles can be identified starting from only the transmissibility measurements. The applicability of the proposed method depends on obtaining varying loading conditions during the experiment.

Maia, Ribeiro, Fontul, Montalvão, and Sampaio (2007) proposed the use of transmissibility with detection and relative damage quantification indicator (DRQ) to detect damage in structures. A DRQ value of 1 or 0 means no damage or damage exist respectively. To conduct the experiments, the responses were measured with seven accelerometers mounted on a beam at various locations. Two shakers were used to excite the beam and two force transducers were used at the excitation coordinates to measure the applied forces. The level of force applied on the beam was changed through various rounds of tests. The effectiveness of the DRQ depends on the Response Vector Assurance Criterion (RVAC) between the damaged and undamaged response vectors. Since the load applied to a structure determines the response generated, a correlation that does not depend on load is needed. Transmissibility was used to generate curves that are not dependent on the applied loads when there was no damage in the beam. As damage increases, the DRQ value reduces below 1 sharply. There is need to investigate the causes of the amount of such deviation.

More recently, Li, Peng, Dong, Zhang, and Meng (2015) developed a technique that is based on transmissibility response measurements to detect and identify the changes in structural damping and stiffness. They investigated the effects of the local variation in stiffness and damping on the TFs and observed that there is a considerable difference between the input force and the variation in stiffness and damping. The authors developed a new damage indicator that is based on the differences between TFs before and after the variations in stiffness and damping. Several simulations were conducted to validate the damage detection indicator. In addition, factors such as the position of the applied force, frequency bandwidth and boundary conditions were determined to influence the performance of TFs (Li, Peng, Dong, Zhang, and Meng, 2015). The proposed damage indicator was shown to be effective in the detection of variations in both damping and stiffness. Notwithstanding, the reduction of the impact on the transmissibility of these factors needs more attention.

3.1.4 Damping

According to Keye, Rose, and Sachau (2001), the modal damping factors may be a more sensitive parameter to damage in delaminated composite structures than the natural frequencies. For example, in order to grasp the correlation between modal parameters and the level of damage in composite materials, (Shahdin, Mezeix, Bouvet, Morlier, and Gourinat, 2009) conducted an impact test on carbon fibre entangled sandwich materials in order to understand the correlation between the damage level density and modal parameters. They conducted vibration tests on damaged and undamaged specimens, monitored the changes in the modal damping factors before, and after the damage was initiated. Heavy and light entangled sandwich materials were used. The heavy specimens have 2.5 times more resin than the light specimens do. The results showed that due to the better damping characteristics, the lighter materials are more sensitive to damage compared to the heavy materials. It was concluded that damping shows more sensitivity to damage than changes in stiffness. Therefore, it is suggested the use of damping as a damage indicator for SHM purposes in composite materials (Shahdin, Mezeix, Bouvet, Morlier, and Gourinat, 2009).

Montalvão, Ribeiro, and Duarte-Silva (2009) proposed the use of the Damping Damage Indicator (DaDI) based on changes in the modal damping factors between undamaged and impact damaged CFRP laminates for the localisation of damage. The authors claim that this is a cost-effective approach since, in principle; only two transducers are needed, although more may be necessary to improve the reliability of the modal identification process. For this is an EMA based method, a force transducer is needed to measure the force at the excitation coordinate. A Laser Doppler Vibrometer was used to measure the responses at four different coordinates. However, the uncertainty involved in the modal identification process of the modal damping factors still constitutes a hindrance to its application.

In order to circumvent the problem with the identification of the modal damping factors in lightly damped structures, (Montalvão, Ribeiro, and Duarte-Silva, 2011) proposed a Multi-parameter Damage Indicator (MuDI) that makes use of a weighted combination of both the modal damping factor and natural frequency changes. They introduced damage in two different sets of CFRP laminate plates with different lay-ups (quasi-isotropic and orthotropic). Damage was introduced following a quasi-static approach (Herb, and Couégnat, 2010; Othman, Abdullah, Ariffin, and Mohamed, 2014; Rilo, Ferreira, and Leal, 2006; Sutherland and Guedes Soares, 2012; J Zhang and Zhang, 2015; Jianyu Zhang, Zhao, Li, and Chen, 2015) and was measured based on the quantity of energy released during the procedure. The results from numerical simulations and experimental tests show that there is a good agreement between the MuDI and damage in the composite laminates. In another work, it was also found that as the damage progressively increases, the modal damping factors increases too (Montalvão Diogo, Dimitris Karanatsis, António MR Ribeiro, Joana Arina, 2014). However, the authors observed that despite the approximately direct proportionality relationship between structural damping and damage, the changes of the individual modal damping factors are not easy to determine.

In an attempt to enhance the precision of the assessment of the modal damping factors, Montalvão and Silva (2015) have recently proposed a novel method that is based on the amount of energy released per cycle of vibration of a material. In order to determine the effectiveness of the method, both numerical and experimental studies were conducted. The results of their study show that the proposed method is suitable for lightly damped systems with well-spaced modes (Montalvão and Silva, 2015). However, it has not yet been shown if this improves or not the accuracy of the location of the damage in CFRPs when using either the DaDI or the MuDI.

Furthermore, Gonilha, Correia, and Cunha (2013) presented modal identification, experimental tests on a glass fibre reinforced plastic (GFRP)-concrete hybrid footbridge prototype that is made of a thin fibre reinforced deck and two GFRP girders. First, they excited the deck with an impact hammer and measured the FRFs. Next, they determined the mode shapes, vibration mode frequencies, and damping ratios using input-output modal identification based on the method of rational fraction polynomial, and output-only response data. Finally, they compared the experimental data with both analytical and numerical simulations to determine the effectiveness of the simulation tools for the GFRP-concrete structures. They confirmed that the comparison of experimental data with both analytical and numerical simulations shows that these models are suitable for the early stage of design to detect possible damages on time. However, an experimental modal identification of a comprehensive prototype is necessary.

Also, Kiral, Içten, and Kiral (2012) studied the effect of impact failure on the damping ratio and natural frequency of woven-epoxy beams. In their work, varied sizes of damage at various locations on the beam were introduced by impact tests. A non-contact vibration measurement system was used to record the free vibration responses, and the damping ratios were determined using the exponent of the free vibration envelope and logarithmic decrement. Their results show that the damping ratio increases as the damage level increases and the natural frequencies are less sensitive to damage. However, the sensitivity of damping ratio depends on the proximity of the damage location to the clamped edge of the specimen.

3.1.5 Lamb Waves

Lamb waves for damage detection have been used for decades and have received much attention from researchers. The application of Lamb waves for damage detection in composite materials commenced between the late 1980s and early 1990s Kessler, Spearing, and Soutis (2002). For example, Su, Ye, and Lu (2006) reviewed Lamb-wave-based damage detection methods for composite materials. They also discussed the propagation mechanisms of Lamb waves in composite materials, modelling and simulation, choice of the relevant mode, data collection and signal processing.

Lamb waves can be described as elastic disturbances that travel through thick solid plates without a significant decay in intensity (Lee and Yoon, 2016). The two types of Lamb wave modes are symmetric (S_o) and antisymmetric modes (A_o). Also, Kessler, Spearing, and Soutis (2002) used Lamb waves for the detection of matrix cracks, delamination, and through-thickness holes in graphite/epoxy composite test specimens. The strength of penetration of Lamb waves through a material is easily determined by their dispersion curves. The curves show the plot of phase velocity versus excitation frequency and the group velocity versus the excitation frequency. The curves are generated from the antisymmetric Lamb wave solution (Kessler, Spearing, and Soutis, 2002):

$$\frac{\tan\left(\bar{d}\sqrt{1+\zeta^2}\right)}{\tan\left(\bar{d}\sqrt{\xi^2+\zeta^2}\right)} + \frac{\left(2\zeta^2-1\right)^2}{4\zeta^2\sqrt{1-\zeta^2}\,\sqrt{\xi^2-\zeta^2}} = 0 \tag{13}$$

where ξ, ζ, and $\bar{d}$ are the non-dimensional parameters used to describe Lamb wave propagation in isotropic materials. The non-dimensional parameters are as stated:

$$\xi^2 = \frac{C_t^2}{C_l^2};\ \zeta^2 = \frac{C_t^2}{C_{phase}^2};\ \bar{d} = \frac{k_t t}{2} \tag{14}$$

where c_t, c_l, c_{phase}, k_t and t are transverse (shear) wave velocity, longitudinal (pressure) wave velocity, phase velocity, wave number, and time, respectively. These velocities depend on the material properties and can be defined by the Lamé's constants (Lamb, 1917):

$$\mu = \frac{E}{2(1+\nu)}; \qquad \lambda = \frac{E\nu}{(1-2\nu)(1+\nu)} \tag{15}$$

$$c_t^2 = \frac{\mu}{\rho}; \qquad c_l^2 = \frac{(\lambda+2\mu)}{\rho}\ ; \ k_t = \frac{\omega}{c_t} \tag{16}$$

where ν is the Poisson's ratio, ρ is the density, ω is the angular frequency, E is the Young's modulus and μ and λ are the Lamé's constants. These equations are important because they show that the Lamb wave propagation mechanisms ultimately depend on the constituent material properties, reason why they have been proposed by some authors to be used as SHM sensitive features. The results obtained from Kessler, Spearing, and Soutis (2002) experiments, indicate that Lamb waves are more sensitive to the local impact of damage in composites when compared to the use of FRFs, as they can provide more information on the characteristics of incipient damages. Lamb wave based damage detection methods provide better information at low frequencies than at high frequencies, typically in the range of 1 to 10MHz (Su and Ye, 2009). Despite their capability to detect damage, they have some limitations. An active driving system is required to propagate the waves through the structure and the data are relatively complex to interpret (Kessler, Spearing, and Soutis, 2002). However, they are suitable for the *in situ* detection and location of damage in composite materials, and can possibly locate damage due to the nature of their local response (Kessler, Spearing, and Soutis, 2002). In addition, Cawley and Alleyne (1996) discussed how to excites and receives suitable Lamb mode(s) for a better data representation.

Diamanti, Soutis, and Hodgkinson (2005) inspected a monolithic and sandwich composite beam. The authors generated A_o modes at 15 kHz and 20 kHz using piezoelectric transducers (PZT) and further applied to identification of delaminations, matrix cracking, and broken fibres. The results showed that damage in the sandwich composite beam and CFRP beam were detected and located effectively. However, they suggested the combination of Lamb waves and ultrasonic C-Scan techniques to quantify damages.

Yang, Ye, Su, and Bannister (2006) adopted finite element models with explicit dynamic analysis to investigate excitation, data collection methods and transport phenomenon of Lamb waves through composite materials. They used various models of piezoelectric actuator/sensors to measure effective shear forces, effective displacements, and effective bending moment excitation modes. The numerical simulations show that the adopted models for both S_o and A_o modes produce consistent results. Nonetheless, even if the sensor model was not suitable for the shear horizontal mode, it was able to determine the symmetric and antisymmetric Lamb wave modes.

Ng, and Veidt (2009) proposed the use of an *in situ* method based on Lamb wave technique to monitor and locate damage in fibre reinforced composite laminates. The exact location was detected through a graphical representation. They scanned damaged and undamaged specimens using networks of transducers. The cross-correlation between the excitation pulse and the envelope of the scattered signal was analysed to reconstruct a damage localisation image. The obtained results showed that the proposed technique could effectively detect and locate damages that are within the area of the network of sensors in the composite laminates. However, the method was not applied to a composite complex structure; further study is needed.

With the intent of increasing the effectiveness and accuracy of Lamb waves for the identification of delamination in composite laminates, Hu, Liu, Li, Peng, and Yan (2010) examined the impact of the Lamb wave excitation frequency on the strength of the signals reflected due to delamination in CFRP laminates. In their research, the authors chose the A_o mode to enable them to detect minor damages. Since within a low frequency band the wavelength of the A_o mode is smaller than the wavelength of the S_o mode, A_o mode is more sensitive to minor damages such as transverse cracks and delamination in the composite laminates (Hu, Liu, Li, Peng, and Yan, 2010; Kessler, Spearing, and Soutis, 2002; Ning Hu, Shimomukai, Fukunaga, and Zhongqing Su, 2008). Hence, Hu, N., Liu, Li, Peng, and Yan, (2010) investigated the generation and relationship of the $A_o$wave mode with the delamination at various frequencies. It was confirmed that there was at least one optimal excitation frequency that produces the reflected signals with the highest intensity from the delamination. The results revealed that the optimal excitation frequencies are all within the range of the natural frequencies of the local delaminated areas like the pure flexural vibration modes – the deformation pattern of the A_o mode.

Okabe, Fujibayashi, Shimazaki, Soejima, and Ogisu (2010) evaluated the characteristics of the broadband of Lamb wave generation using a system that incorporates macro fibre composite (MFC) actuators and fibre Bragg grating (FBG) sensors. The MFC generates the Lamb waves into the composite laminates and the FBG is used to collect the emitted signals for analysis. They separated the Lamb waves in the composite laminate into S_o and A_o modes by using MFCs that are localised together to excite the Lamb waves and using two FBGs installed on the laminate as receivers. Both experimental and numerical analysis was conducted to confirm the proposed technique. The results showed that the method could be used in detecting the size of a delamination in a CFRP quasi-isotropic plate. Although the authors could detect delamination, other types of damages in composites were not analysed.

Manson, Worden, Monnier, Guy, Pierce, and Culshaw (2011) decided to publish the studies they conducted between 1998 and 2001 on damage assessment in smart composite structures because of the applicability of their findings. Their studies were phased in two stages: (i) the evaluation of the suitability of Lamb waves for damage inspection in composite plates and (ii) the assessment of the application of novelty detection based on Lamb wave scattering for detecting minor damages in composite plates. A novelty detection is based on the difference between the normal condition of the structure and the measured data (Manson, Worden, Monnier, Guy, Pierce, and Culshaw, 2011). Damage was introduced on a square CFRP plate with a 0° - 90° weave of fibres, by drilling several holes. At the final stage, they introduced BVID, characterised by an internal delamination, through a controlled impact on the composite laminate. $5-$ cycle tone bursts at 280 kHz and 115 kHz were used to excite the S_o and A_o modes respectively. The Lamb waves were generated from a piezoelectric disc. The results obtained showed that Lamb waves are effective in detecting considerably small damages in composite laminates. However, changes in the environment of the structure, operating conditions, like temperature and moisture (Tjirkallis and Kyprianou, 2016) or variation in the instrumentation, have a strong impact on the accuracy of the damage detection method.

The effectiveness of the A_o mode in detecting small damages within low frequencies in composite materials has increased its application in SHM. Mustapha, Ye, Wang, and Lu, (2011), used A_o modes to estimate debonding in a sandwich (with a core) carbon fibre/epoxy plastic (CF/EP) composite structures. Sandwich structures usually are lightweight, possess high bending stiffness and have excellent dynamic properties (Mustapha, Ye, Wang, and Lu, 2011). These properties have increased their applicability in the construction, aerospace, and manufacturing industries.

Unfortunately, impact loads tend to initiate, debonding between the core at the centre and the two faces that sandwich it, thereby reducing the component's mechanical properties. No matter how small the defects at the skin-stiffener connection are, they can influence the performance of the structure (Ooijevaar, Rogge, Loendersloot, Warnet, Akkerman, and Tinga, 2015). The primary limitation of a sandwich structure is that it hides defects, which makes it difficult to detect damage through visual inspection and many other NDT methods. (Mustapha, Ye, Wang, and Lu, 2011) investigated the impact of the size of debonding on the delay in time of flight (ToF) and energy of the reflected signals of the A_o mode of low frequency in the sandwich of CP/EP composite beams. In their study, they initiated debonding in the beams at varying locations. They used an active signal generation to activate the signal and a data acquisition system was used to collect Lamb wave signals for analysis. A $5-$ cycle sinusoidal toneburst was generated and the Lamb waves were collected by a PZT sensor. In their work, they could locate debonding using the ToF of the waves reflected by the damage. The results show that A_o modes can be used to determine debonding in sandwich composite beams in the low frequency ranges of 0 to 30 kHz. However, the correlation between the level of debonding and the ToF of the waves reflected by damage (debonding) is not unique.

Zhao, Royer, Owens, and Rose (2011) assessed the health of structures by observing the deviation of Lamb waves during propagation through the structure. The areas where the deviations occurred were mapped out based on ultrasonic Lamb wave tomography imaging. The result shows that tomographic imaging enables the Lamb waves to visually represent and monitor damage in structures.

Ben, Ben, Vikram, and Yang (2013) suggested the use of ultrasound-based Lamb wave propagation to locate and assess damage in composite materials. The presence of damage in a structure would cause the Lamb waves to deviate from its path of propagation, which is normally in a straight path, affecting its intensity too. This means that the size of Lamb waves excited into a damaged structure is reduced when extracted from the receiving end for analysis. This was the idea behind (Ben, Ben, Vikram, and Yang, 2013) research work. Their results show the effectiveness of ultrasound-based Lamb wave method for damage detection in composite structures, as confirmed by several other researchers (Carboni, Gianneo, and Giglio, 2015; Ramadas, Padiyar, Balasubramaniam, Joshi, and Krishnamurthy, 2011; Rathod and Roy Mahapatra, 2011).

Keulen, Yildiz, and Suleman (2014) proposed a sparse network that can identify damage over a wide range of the composite material. They utilised an algorithm that considers the damage progression history in composite materials for better damage identification in structures. The method used a hexagonal arrangement of 12 PZTs, against the dense network of transducers that is usually necessary to monitor larger areas. The Lamb waves were actuated by one of the transducers through the test specimen and other transducers were used to receive and collect the data. The results showed that the inclusion of damage progression history increased the efficiency of identifying possible damage within a range of 12 mm of the confirmed damage to the material. However, the application of this method is time consuming.

Carboni, Gianneo, and Giglio (2015) studied how Lamb waves travel through materials to design a single mode of propagation method for damage identification. This method would ease the interpretation of Lamb waves. A CFRP laminate was used for the experiment. They characterised the elastic properties and the scattering behaviour of Lamb wave propagation through the composite laminate. A statistical approach was used to determine primary factors affecting the sensitivity response against artificial and natural delamination in a composite laminate. One of the results obtained suggest that the analysis of the elastic signal waves received by PZT sensors could be simplified by actuating the Lamb waves within the frequency range of 0 - 50 Hz.

More recently, Mustapha, Ye, Dong, and Alamdari (2016) used guided ultrasonic wave signals based on a pitch and catch configuration of PZT actuator and sensors to determine the size of BVID in CF/EP sandwich beam and panels introduced by a step-wise quasi-static indentation. They used the deviations in the characteristics of A_o and S_o modes and correlated them with the damage size. Three PZTs were installed on the test specimen: one was used as the actuator and the remaining two as sensors. A tone burst of $60\ Volt$ confined in a Hanning window serves as the input signal for the actuator. It was seen from the results that residual deformations on the skin were about the same to the extent of the dent and the damaged location within the honeycomb core. Again, the two modes of Lamb waves were sensitive to even a 0.2 mm size of a dent on the composite laminate.

3.2 Acoustic-based

3.2.1 Acoustic Emission

According to Mba and Rao (2006), acoustic emission (AE) was originally developed as a technique for non-destructive testing (NDT) to monitor and sense cracks in structures and materials. Sensors are used to pick up and analyse the attributes of transient elastic waves (stress waves) generated by crack growth and propagation (Carpinteri, Lacidogna, Accornero, Mpalaskas, Matikas, and Aggelis, 2013; Yun, Choi, and Seo, 2010). When loads are exerted on a structure that has a crack, the crack may generate stress waves, which are picked up by the AE sensor mounted on the surface of the structure, as illustrated in the schematic example in Fig. 3.2.

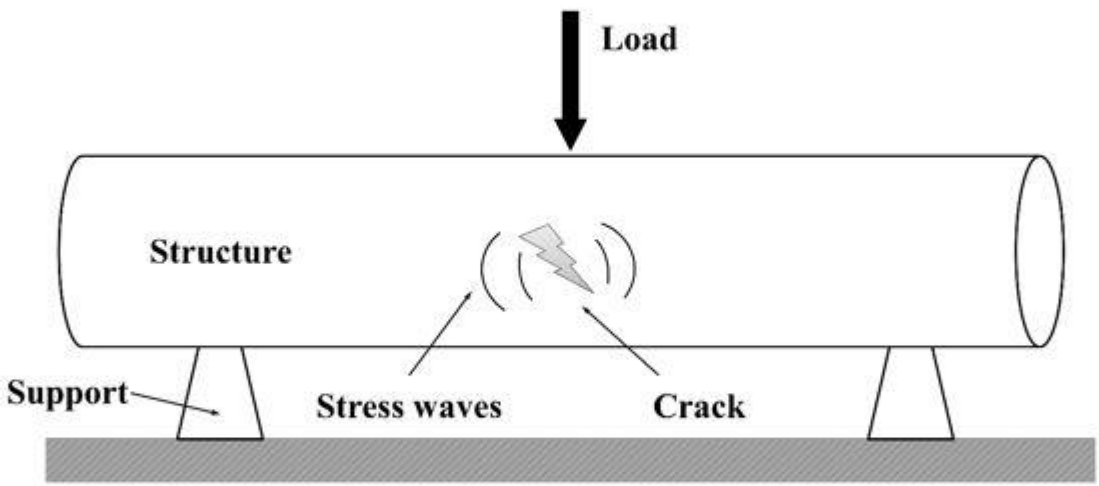

Figure 3.2 Stress waves due to the presence of crack in a material under stress.

AE is highly sensitive to the development of damage in composite structures. However, in order to explore the full potential of AE in SHM applied to composite materials, the velocity and attenuation of sound wave propagation in composite materials should be known. AE techniques can be used to study the damage propagation and characterise its failure mechanisms in composite structures (Selman, Ghiami, and Alver, 2015). Researchers like Mechraoui, Laksimi, and Benmedakhene (Mechraoui, Laksimi, and Benmedakhene, 2012) analysed the propagation and the evolution of velocity of acoustic waves in glass/epoxy composite materials. In their study, after conducting a static bending test, they analysed the damage mechanisms based on amplitude correction. They measured the real velocity based on the difference between the arrival times of each signal and the location of sensors in order to localise the different mechanisms of damage on the specimen such as delamination, crack, and the fibre break. The measured velocity was compared with the value of the theoretical velocity determined with theoretical model analysis. The AE was able to localise the introduced damages on the composite plate. However, based on attenuation curve, amplitude correction can be used to enhance the localisation of damage in the test specimen. With this method, the amplitudes of the signal can be obtained without attenuations. See more information in (Mechraoui, Laksimi, and Benmedakhene, 2012).

Liu, Chu, Liu, and Zheng (2012) studied the damage growth and the failure mechanisms in carbon fibre/epoxy composite laminates having different lay-up patterns with holes at their centres using AE techniques. They extracted representative features such as counting, energy, and amplitude with the load history in order to investigate failure mechanisms of composites. Their work was not comprehensive, as they only tried to establish the true mapping between the AE responses and properties of failure of composites. Their research does not consider impact damage, but only focused on composite laminate with holes.

Yun, Do, Choi, and Seo (2010) investigated the suitability of the AE approach to monitoring the damage progression in reinforced concrete (RC) beams strengthened in flexure with CFRP sheets. Their aim was to develop a health monitoring method based on AE techniques for RC structures that are strengthened with CFRP sheets. They considered the effectiveness of the strengthening based on the numbers of layers of CFRP sheets and the imperfections of the construction. In order to simulate imperfection in the construction, the CFRP was bonded without adhesive inside 10% and 20% area of the bonding area of the CFRP sheets. The AE signals were extracted and studied for all test specimens. The results of their analysis show that, depending on the active mechanism of damage, the characteristics of the signal – event, amplitude versus duration and amplitude versus frequency - has differences in the various stages of loading.

Also, Noorsuhada (2016) conducted an extensive review of the use of AE techniques for the assessment of fatigue damage in RC structures. From the review, it was identified that fatigue damage test of RC structures based on increasing fatigue load is limited, and AE analyses such as intensity analysis, AE parameter analysis is limited. Aggelis, Barkoula, Matikas, and Paipetis (2012) studied the fracture behaviour of composite cross-ply laminates using both ultrasonic and acoustic techniques. In their study, they use tension-tension fatigue and incremental loading until the specimen failed. The results show that AE activity is highly related to the accumulation of damage in incremental tensile step loading. The results from the numerical simulation indicate that damage isolates the distinct layers due to the specific geometry of laminates. Huang, Zhang, and Li (2013) suggested an approach for the localisation of AE in a marble stone using distributed feedback (DFB) fibre lasers, with the objective of identifying damage in civil structures.

In order to increase the effectiveness of the AE technique for SHM in textile reinforced cement (TRC), Blom, Wastiels, and Aggelis (2014) relate acoustic emission parameters to the mechanisms of fracture that contributed the most to the failure of the composite laminate. The primary parameters of AE signals are the activity, a total number of events, and energy (Bobrov and Stepanova, 2013). Hamdi, Le Duff, Simon, Plantier, Sourice, and Feuilloy (2013) extracted suitable damage descriptors using the Hilbert-Huang transform (HHT) for the understanding of AE patterns. This approach contributed to the understanding of damage evolution in structures. It provided relevant results for the extraction of non-stationary acoustic emission waves. Again, Blom, El Kadi, Wastiels, and Aggelis (2014) monitored the flexibility of TRC laminates using AE technique. They observed that AE was able to monitor the failure mechanisms and also identify the stress field. Bravo, Toubal,

Koffi, and Erchiqui (2015) used the AE technique to examine the process of damage evolution in bio and green composites. Recently, Fotouhi, Suwarta, Jalalvand, Czel, and Wisnom (2016) investigated the relationship between the corresponding damage mechanism in thin-ply unidirectional carbon/glass hybrid laminates undergoing tensile loading and AE events. In their work, they established a criterion that is based on the values of energy and amplitude to identify the fragmentation failure mode. The evolution of damage in the test specimen was monitored with the cumulative amount of the AE signals. It was concluded that the method can be used to characterise the mechanisms of failure in hybrid laminates and can detect damage initiation and propagation.
Akil, De Rosa, Santulli, and Sarasini (2010) compare the notch and flexibility of pultruded jute/glass and kenaf/glass hybrid polyester composites by monitoring them with acoustic emission technique. Pultrusion is a technique used for the fabrication of composite materials with a better reinforcement, tensile strength, and consistent quality (Baran, Tutum, Nielsen, and Hattel, 2013)(Carlone, Baran, Hattel, and Palazzo, 2013)(Novo, Silva, Nunes, and Marques, 2016). Aymerich and Staszewski (2010b) established the use of the nonlinear acoustic technique for detection of impact damage in composite laminates. They introduced a high-frequency acoustic wave to a piezoelectric sensor at a location on the composite and receive it with another sensor. An electromagnetic shaker was used to excite a low-frequency flexural mode to induce damage. A pattern of sidebands close to the acoustic harmonic in the power spectrum indicates the damage caused by the impact on the specimen. It was confirmed that there is a linear relationship between the magnitude of the sidebands and the severity of damage in the specimen. However, they observed that the responses to different boundary conditions for the healthy and damaged specimens were not uniform. Further studies were required to identify and characterise the non-damage related nonlinearities.

3.2.2 Ultrasonic Inspection

Ultrasonic inspection methods are capable of detecting defects (delamination, porosity, crack, etc.) and providing mechanical properties (e.g., anisotropic elastic constants) on composite materials after the damage has been introduced (Potel, Chotard, de Belleval, and Benzeggagh, 1998).
The multi-layered arrangement of composite laminates makes it quite complex to detect damage when compared to metals. This is due to the anisotropic properties of the constituent materials and a sensitivity to echoes (Ng, Ismail, Ali, Sahari, Yusof, and Chu, 2011). During the damage detection procedure, echoes from the particles from the composite materials disturb the elastic waves from the damage, hence polluting the original signal from the damage. Hence, it is required to filter the unwanted echoes in order to detect any incipient damage in the composite structure.
Matrix cracking in composite laminates has been a source of concern in the engineering industry because it usually is the first flaw to occur. As such, several techniques have been developed to detect and locate them during the initiation stage (Steiner, Eduljee, Huang, and Gillespie Jr, 1995). Aymerich and Meili (Aymerich and Meili, 2000) analysed matrix cracking and delamination in composite laminates through ultrasonic inspection. In their work, they scanned test specimens with ultrasonic oblique and normal incidence in a pulse-echo (or one-sided) mode using a focused broadband transducer. The results indicated that the technique was effective in detecting matrix cracking in the composite. However, the oblique incidence ultrasonic method is more sensitive to matrix cracking, while the normal incidence ultrasonic method is more effective for delamination.

Kinra, Ganpatye, and Maslov (2006) established an ultrasonic backscattering method to detect matrix cracks in ply-by-ply graphite/epoxy composite laminates. The ultrasonic backscattering method uses an oblique incident beam. A SONIX FlexSCAN ultrasonic scanning system was used for the data collection. Results show that the identification of matrix crack in the mid-ply does not depend on the damage in the intermediate plies. In other words, damage in the intermediate plies does not suggest that the middle plies would have damage too. Also, Hosur, Murthy, Ramamurthy, and Shet (1998) used ultrasonic C-scan to detect and map delamination in CFRP laminates. They developed a software called IMPCTDAM to analyse the raw images from the C-scan and quantify the level of damage. A C-scan enables the determination of the thickness of the material, damage location and possibly the severity of the damage in it (Hasiotis, Badogiannis, and Tsouvalis, 2011). In their work, they made some general assumptions based on their results: the impact damage increases as the depth increase until it attains maximum size; the behaviour of the composite laminate undergoing compression and buckling due to impact loading can be studied using data from the maximum delamination and its position, etc.

Ng, Ismail, Ali, Sahari, Yusof, and Chu (2011) applied the ultrasonic technique to investigate delamination in multi-layered glass reinforced plastics. The defect in the glass fibre reinforced laminate was detected and located with a single transducer based on pulse-echo mode, and the signal-to-noise ratio (SNR) was enhanced with the use of a split spectrum processing (SSP) method in order to achieve a clear representation of the signal from the damage in the laminates. The SSP conditioners filter the interfering echoes from the particles of the constituent laminates. The technique is based on the analysis of the frequency of the signal spectrum.

In another application, Sharma, Sharma, Sharma, and Mukherjee (2015) reaffirmed the effectiveness of the ultrasonic inspection technique in damage detection, by using it to monitor the initiation and evolution of corrosion in concrete reinforcing bars in concrete after being repaired with glass and carbon fibre sheets. The results obtained show effectiveness of the ultrasonic guided waves to monitor the evolution of corrosion in the test structure. Although their study was conducted at a laboratory scale, it is claimed that it can be extended to a full-scale structure by scaling up the ultrasonic pulse energy.

3.2.3 Acousto-Ultrasonic

Acoustic-ultrasonic (AU) based methods uses two ultrasonic sensors, each located at different points on the test specimen. AU methods are NDE techniques developed around the late 1970s to determine the mechanical properties of composite structures (Vary, 1981; Vary and Bowles, 1978). One of the sensors serves as an actuator used to initiate the ultrasonic wave through the test material, whereas the other is the receiver of the reflected AU transient stress wave used for analysis. A pulsing PZT initiates broadband ultrasonic stress waves in the test specimen (Gyekenyesi, Morscher, and Cosgriff, 2006; Loutas and Kostopoulos, 2009a). This technique measures the relative efficiency of AU signal propagation across the test material (Barbezat, Brunner, Huber, and Flueler, 2007). The presence of damage in a material reduces the strength of the AU signal that is transmitted through it. Gyekenyesi, Morscher, and Cosgriff (2006) used the AU technique to investigate the presence of damage and stress levels in two ceramic composites under loading, unloading, and reloading tensile tests. Their aim was to show the possibility of using AU as an in-situ NDE technique for damage monitoring for two types of silicon carbide fibre/silicon carbide matrix (SiC/SiC) composite systems and stress dependence of the AU method. They loaded the test samples mechanically in the load/unload/reload runs to determine the impact of stress levels on the AU waves. The results indicated that the enhanced matrix composite labelled HN-C-ENH has a higher transverse crack density than the standard matrix composite, HN-C-STD. From the analysis of AU parameters, the mean square value of the power spectral density was able to monitor the accumulated damage more consistently Gyekenyesi, Morscher, and Cosgriff (2006). In addition, the AU measurements related to the HN-C-ENH composites did not indicate stress dependence, whereas the AU measurements related to the HN-C-STD version did (Gyekenyesi, Morscher, and Cosgriff, 2006).

Loutas and Kostopoulos (2009a) monitored the evolution of damage in carbon/carbon (C/C) reinforced composite laminates that are subjected to loading, unloading, and reloading, using AU based methods. The comprehensive details of the experimental method and material characterisation can be found in (Loutas and Kostopoulos, 2009b). A pulse generator and a transducer were used to introduce the AU stress waves into the test specimen. A similar transducer was used to collect the reflected AU stress due to the applied load. It was confirmed that the AU technique is suitable for monitoring the damage evolution in composite materials, including delamination (Chrysochoidis, Barouni, and Saravanos, 2011). The scope of their research was restricted C/C woven composites, other forms of composite laminates need to be analysed.

Loutas, Vavouliotis, Karapappas, and Kostopoulos (2010) investigated the efficiency of AU measurements in the development of damage in CFRP laminates during fatigue tensile loading. Damaged and undamaged composite laminates were used for the experiment, to compare the deviations in the measured parameters. They CNTs to modify the epoxy matrix of quasi-isotropic carbon fibre reinforced laminates. The aim was to monitor the accumulation of damage in the test specimens during fatigue. In their work, they also tested four composite specimens with the measurement of AU signals at 80% stress level of the maximum tensile stress. The idea was to confirm if the AU wave parameters separated from the emitted signals change in a monotone manner, which could be a pointer to the evolution or accumulation of damage in the laminate. The authors were able to monitor the initiation, evolution, and the accumulation of damage during the fatigue tests. However, further investigation is required to expand the applicability of the method.

Torres-Arredondo, Tibaduiza, McGugan, Toftegaard, Borum, Mujica, Rodellar, and Fritzen (2013) applied AU for the detection and classification of damage to CFRP sandwich structures. They mounted four transducers separated at equal distances on the surface of the test specimen and introduced varying types of damage on the test specimen. The authors used an excitation signal of 12 Hanning windowed cosine train signal with 5-cycles and a 50 kHz carrier frequency in order to boost the propagation efficiency of the AU signals through the material. In their study, a method that is based on hierarchical nonlinear PCA, square prediction measurements, and self-organising maps, was applied in order to detect and locate damage. The technique was also able to characterise fatigue damage in aluminium plates (C. Zhou, Hong, Su, Wang, and Cheng, 2013). The researchers only focused on sandwich structures such as carbon fibre plastic and glass fibre plastic sandwich structures; application of the technique on other composite structures would be plausible.

3.2.4 Vibro-Acoustic

Vibroacoustic modulation techniques are highly sensitive to the presence of nonlinearities (Yoder and Adams, 2010). In the vibroacoustic modulation technique, the structure is excited with a pumping signal while it is simultaneously interrogated with a more sensitive probing signal (Yoder and Adams, 2010). According to Aymerich and Staszewski (2010a), vibroacoustic techniques are sensitive to cracks in structures (Yoder and Adams, 2010). Hence, several researchers have used this technique to detect fatigue cracks in metallic structures effectively (Dutta, Sohn, Harries, and Rizzo, 2009; Kim, Adams, Sohn, Rodriguez-Rivera, Myrent, Bond, Vitek, Carr, Grama, and Meyer, 2014; Ryles, Ngau, Mcdonald, and Staszewski, 2008), but application in composite structures still is limited (A. Klepka, Pieczonka, Staszewski, and Aymerich, 2014). Aymerich and Staszewski (2010a) monitored low impact damage in a rectangular laminated composite plate. They excited the composite plate with a constant amplitude probing signal and slow amplitude-modulated vibration pumping signal simultaneously. The pumping signal was introduced to the specimen with an electromagnetic shaker. Experimental results indicated the amplitude of the sidebands is related to the amount of damage in the plate. However, more study is required to determine the sensitivity of the method to different forms and severities of damage in composite laminates.

Klepka, Staszewski, di Maio, and Scarpa (2013) used a nonlinear vibroacoustic modulation to detect damage in composite chiral sandwich panels. The authors used low-profile PZTs to actuate the ultrasonic wave in the test specimen, and an SLDV to acquire the vibroacoustic waves. The results show the effectiveness of this technique in detecting debonding between the composite surface and the chiral core, which was verified by a classical vibrothermographic analysis (Klepka, Staszewski, di Maio, and Scarpa, 2013) and is in agreement with the results presented in (Aymerich and Staszewski, 2010a). Unfortunately, the vibrothermographic test could not detect damage in its early stage, except large when the damage increases; which may be due to poor sensitivity. In addition, Sarigül and Karagözlü (2014) examined the impact of the type of composite material, the number of layers and orientation of ply on the coupled vibroacoustic properties of plates – their natural frequencies - by conducting a regression analysis. However, they only conducted numerical analysis, without validating their results with experiments. Hence, numerical analysis alone would not be sufficient to make a conclusion.

Klepka, Pieczonka, Staszewski, and Aymerich (2014) also studied the effect of low and high-frequency excitations in non-linear vibroacoustic. The authors observed the nonlinear modulations in ultrasonic waves due to damage in composite chiral sandwich panels using high frequency ultrasound and low-frequency modal excitations. The spectra of the signal response indicated only the frequency components related to the propagating ultrasonic wave and the low-frequency excitation when the specimen is undamaged. In the presence of damage, there are additional sidebands around the two main ultrasonic components (Aymerich and Staszewski, 2010a; Klepka, Pieczonka, Staszewski, and Aymerich, 2014; Klepka, Staszewski, di Maio, and Scarpa, 2013; Yoder and Adams, 2010). The level of damage in the structure relates to a number of sidebands and the amplitude of the sidebands depends on the intensity of modulation. Nonetheless, when analysing damage identification a careful selection of both low and high frequency excitation is necessary. This requires some expertise in order to choose the right values. Furthermore, more research is required to determine the impact of the resonance frequency of the local defect on the enhanced nonlinear vibroacoustic modulations.

Likewise, Pieczonka, Ukowski, Klepka, Staszewski, Uhl, and Aymerich (2014) detected BVID in light composite sandwich panels using the nonlinear vibroacoustic modulation method. The authors considered different levels of damage in two damaged and undamaged panels. They were able to detect the severity of damage based on the intensity of modulation (number and amplitude of sidebands). It was observed that as damage increases, the modulation intensity increases. Vibrothermographic inspection of the specimens was used to validate the results from the vibroacoustic analysis. However, there was no explanation of the modulation that are not related to damage. This would require further studies to explain those modulation nonlinearities. Besides, the experiment should be extended to other damage types and complex composite structures.

3.3 Instrumentation-based

3.3.1 Sensor Networks

Due to the continuous technological advancement in the area of SHM, composite laminates can be embedded with sensors in order to enhance effective monitoring and detection of damage initiation and progression. However, this must be done during the manufacturing process and it often compromises the stiffness and strength of the composites. Masmoudi, El Mahi, and Turki (2015) investigated the effects of embedded piezoelectric sensors on the bending fatigue strength of composite laminates. They examined and compared the results from composite laminates with and without embedded sensors using AE to capture and monitor the generated transient elastic waves. A classification *k-means* method was used to evaluate the acoustic signature in order to determine the evolution and various failure modes in composites with and without embedded sensors. It observed that the mechanical behaviour of both types of composites indicates no difference in form, but the composite with embedded sensors was more sensitive to damage than the one where the sensor was mounted to the surface of the structure. Although methods based on embedded sensors are usually cost-effective to implement (Alexopoulos, Bartholome, Poulin, and Marioli-Riga, 2010), care must be taken to avoid excessive weight and reduced mechanical properties of the composite materials, since the embedded network of sensors will be part of the structural component.

Ghezzo, Starr, and Smith (2010) investigated the effect of integrated sensors on the integrity and mechanical response in fibreglass epoxy laminates. In their work, monotonic tensile tests on fibreglass epoxy laminates were conducted to monitor the initiation of damage and detect damage. From the results, it was shown that the initiation of debonding starts at the bond between the implanted sensor and the composite resin. Due to the high-stress levels, cracks occur around the specimen. They concluded that, although integrating a sensor network in composites is feasible and effective for damage identification, care must be taken in the design of the sensor, the method of integration, data collection, signal processing and analysis, and the estimation of the changes in the mechanical performance due to the presence of embedded sensors (Ghezzo, Starr, and Smith, 2010). Nonetheless, their research was conducted in a controlled environment – laboratory. Hence, before drawing any conclusion the method needs to be implemented in-situ.

Alexopoulos, N. ., Bartholome, C., Poulin, P., and Marioli-Riga (2010) integrated conductive CNT fibres to nonconductive GFRP test specimens in order to determine the behaviour of the material under different loading conditions by measuring the variations in the electrical resistance on the CNT fibre. They correlated the response of the GRFP to mechanical load and the electrical resistance measurements of the embedded CNT fibres to monitor and detect damage. The correlation between the two parameters depends on the loading history of the material. According to the authors, the advantage of using CNT fibres is that they are easy to insert and do not reduce the mechanical properties of the material. Based on their results, it was concluded that the CNT fibres have a better sensing and damage monitoring capability of non-conductive composites than embedded carbon fibres and modified (doped) conductive matrices. Having embedded CNT fibre in GFRP, it would be good to consider CFRP coupons with embedded CNT fibre for further investigation.

Ksouri, Matmat, Boukabache, Escriba, and Fourniols (2011) installed an accelerometer sensor network on a composite laminate to examine the response of the composite structure to an impact load. In their work, they introduced shock propagation waves through the network of accelerometer sensors. The idea was to compare the responses received from the accelerometers before and after the initiation of damage. The results indicate that the method was suitable for the detection of damage to the composite structure. However, the method was unable to localise damage in the system.

Giurgiutiu and Santoni-Bottai (2011) examined the advantages of the use of embedded piezoelectric wafer active sensors to impart and receive elastic waves for damage detection and localization in unidirectional and quasi-isotropic composite plates. While some conventional ultrasonic transducers function through the application of vibration, pressure on the test surface, the piezoelectric wafer active sensors function through surface pinching and are strain coupled with the surface of the structure (Giurgiutiu and Santoni-Bottai, 2011). The authors claim that this improves the performance over ultrasonic transducers in the transmission and reception of elastic stress waves. In addition, piezoelectric wafer active sensors are less expensive, lightweight and can be used for SHM in large structures.

Nauman, Cristian, and Koncar (2011) conducted a three-point bending tests on multilayer composite laminate specimens with two embedded sensors at different locations in order to determine the behaviour of the material during bending. The sensors are positioned in such a way that they can monitor compression and traction deformations in the material and can also detect the matrix fracture initiation and propagation (Nauman et al., 2011). The embedded sensors were able to generate the stress-strain history of the test specimens. The results from the three-point bending test provide information on the health of the specimen and data related to the propagation of the crack, delamination, and fracture inside the material under quasi-static loading. However, there needs to be an improvement of the sensor's sensitivity and bandwidth and compatibility between the embedded sensors and with carbon or other multifilament tows that are used as fibre reinforcements.

Dziendzikowski, Dragan, Kurnyta, Kornas, Ł.Latoszek, Zabłocka, Kłysz, Leski, Chalimoniuk, and Giewoń (2014) conducted an impact test on a CFRP laminate with an embedded network of PZT sensors. The aim was to determine the effectiveness of the embedded network of sensors in detecting BVIDs. Three impacts with different energies were applied to the test specimen and the emitted elastic stress waves were received by the PZT network for analysis. The health of the test specimen was determined from the selected signal characteristics known as damage indices. Notwithstanding, apart from damages, other factors such as weather can have an effect on the signal acquired, which can result in a false positive or false negative indications (Dziendzikowski, Dragan, Kurnyta, Kornas, Ł.Latoszek, Zabłocka, Kłysz, Leski, Chalimoniuk, and Giewoń, 2014). In order to avoid that, the authors suggested that there should be a balance between the level of sensitivity of the damage indices to damages and the stability of the damage indices under different working conditions of the PZTs.

Luo and Liu (2014), integrated graphite nanoplatelets (GNPs) into an epoxy/fibreglass composite laminate. The GNP thin fibre sensor enabled to determine the state of the local resin curing in the composite material during the manufacturing process (Luo and Liu, 2014). In addition, it was able to map out the state of stress and strain in the material when under load. The embedded GNPs in the composite laminate make the structure smart, in such a way that it enables the structure to act as a sensor that is capable of self-monitor its damage condition. According to the authors, the GNP fibre sensor is currently only suitable for non-conducting composite materials. Hence, it is yet to be applied to conductive composites such as CFRPs.

Cenek, Mudit, and Radek (2014) conducted a series of tests to detect and locate low energy impact damages in carbon composite materials by embedding piezoelectric sensors in three different layouts at different depths. The sensors were installed on a lean, flexible printed circuit before integrating them into the composite laminates. The results from the experiments show that all the layouts were able to detect the impact energies applied to the test specimens, but the sensors that are close to the surface of the specimen are more sensitive. However, even if the authors were able to detect and locate damage, the method was not sufficient to determine its type and severity.

As mentioned earlier, one limitation of embedding sensors in composite structures is that this may impact on their host's mechanical properties (Lang, Boll, and Schotzko, 2012), for example through the addition of weight. This challenge has engaged several researchers in the attempt to devise means to reduce the weight contribution from the sensors, while at the same time the reliability and durability are not compromised. Through miniaturisation of the embedded sensors, the impact may be noticeably reduced, thereby maintaining the original properties of the composite structure almost unchanged. To this end, (Salas, Focke, Herrmann, and Lang, 2014) designed a miniature wireless sensor network that works through an inductively coupled coil. The authors confirmed the possibility of generating power using inductive coils for a piezoelectric wafer active sensor system in CFRP composites for SHM. However, CFRPs are found to introduce limitations in the power transmission due to the conductive nature of carbon fibres.

Lu, Jiang, Sui, Sai, and Jia (2015) used fibre Bragg grating (FBG) sensors to detect structural dynamic response signals from CFRP structures and extracted the damage characteristic through Fourier transform and principal component analysis (PCA) methods. The dynamic response signal was generated by an active actuation method. From the damage characteristics, acquired, they were able to detect damage with a one-class support vector machine technique and the localization and severity of damage were achieved with multi-class C-support vector classification techniques. In their study, the accuracy of the damage detection was claimed to be above 90%. However, there are challenges associated with the use of FBGs in composite structures. For example, Kinet, Mégret, Goossen, Qiu, Heider, and Caucheteur (2014) reviewed some challenges due to the use of FBGs in composite materials. In their study, they analysed the problems linked to the demodulation of the amplitude spectrum during and after the curing process, the distinction between the effect of temperature and strain, and the relation between the integrated optical fibres and the surroundings.

The presence of micro-cracks in the composite structure tampers with its contour by increasing the surface roughness. Such changes on the surface can be used to monitor the health of structures and detect damage by measuring the surface roughness (Zuluaga-Ramírez, Frövel, Belenguer, and Salazar, 2015). Zuluaga-Ramírez, Arconada, Frövel, Belenguer, and Salazar (2015) measured the surface roughness of CFRP test specimens with a confocal microscope in order to assess the development of surface roughness due to fatigue loads applied on the structure. In their study, loads were applied based on the standard load sequence for fighter aircraft. The authors thoroughly scanned the test samples vertically in order not to miss any point. They ensured that every point on the surface of the test material passes through a pinhole to the focus plane. Results indicated that fatigue loads are the prime culprits that cause surface roughness, affecting the topography of the composite structure surface.

3.3.2 Eddy Currents

Eddy-current based techniques work on the basis of electromagnetism, whereby the conductivity of a material can be detected without having contact with it (Yin, Withers, Sharma, and Peyton, 2009). Khandetskii and Martynovich (2001) applied an eddy-current technique to detect damage near the edges of composite laminates. They used a finite difference method to study a two-dimensional model of carbon reinforced composite material that was made up of alternating layers of the reinforcing fabric and binding material with delamination on a boundary between layers (Khandetskii and Martynovich, 2001). The authors mounted a rectangular eddy-current transducer on the edge of the specimen to generate a vector potential field. The results obtained from the calculations at different widths of the delamination suggest that the modulation pulse width due to damage is almost a linear function of the width of the delamination.

Bonavolontà, Valentino, Pepe, and Bonavolontà, Valentino, and Pepe (2007) recommended the use of an eddy-current method based on a high temperature superconducting quantum interference device (HTS-SQUID) to assess a glass laminate aluminium reinforced epoxy (GLARE) structure. The HTS-SQUID sensor is sensitive to any deviation in the magnetic field due to incipient damage in the composite material even at a low excitation frequency (Bonavolontà, Valentino, Pepe, and Bonavolontà, Valentino, and Pepe, 2007). The authors used a steel impactor to introduce different flaws on the GLARE specimen by changing the level of impact between the range of 5J and 36J. Results showed the effectiveness of the eddy-current method based on the HTS-SQUID magnetometer to analyse the various damage stages in GLARE composites. Additionally, experimental results showed that the mechanical properties of the fibre/metal laminate under stress could be determined using the eddy-current method based on the HTS-SQUID magnetometer.

Furthermore, Bonavolonta, Valentino, Marrocco, and Pepe (2009) expanded the application of eddy-currents to the identification of damage in GLARE composite laminates by using HTS-SQUID and giant magneto-resistive (GMR) sensors. Their aim was to correlate the performance and effectiveness of HTS-SQUID and GMR sensors to detect damage in fibre/metal laminate composite materials. According to the authors, the limitation of the typical eddy currents is related to the decreasing sensitivity of the search coil with the increasing lift-off and tilting of the probe. The choice of the two different sensors was to overcome the primary limitation of the eddy-current technique in damage detection. In their study, a Teflon and wet cotton were used to introduce defects and porosity respectively in the test specimens. The results show that the HTS-SQUID sensor has a higher sensitivity to the porosity inside the test specimen than the GMR sensor, due to its larger magnetic field. Additionally, the eddy current method using HTS-SQUID first order gradiometer and the GMR second order gradiometer were able to detect internal flaws in multilayers metallic alloys.

Yin, Withers, Sharma, and Peyton (2009) designed three multifrequency eddy current sensors to measure the bulk conductivity, characterise directionality, detection of fault and imaging of unidirectional, cross-ply, and impact damaged CFRP specimens. The authors simulated the sensor responses with both analytical and finite element models. From the results achieved, (Yin, Withers, Sharma, and Peyton, 2009) claimed that the characterisation of CFRP specimens with an instrument that is based on eddy current principles is feasible.

Mizukami, Mizutani, Todoroki, and Suzuki (2015) presented the induction heating assisted eddy current testing (IHAET) for the detection of delamination in thermoplastic CFRPs' welded areas. Delamination may develop in CFRPS during welding due to several reasons, for instance: expansion of entrapped air, an insufficient squeeze of air in the bond line due to insufficient pressure and thermal stresses (Mizukami, Mizutani, Todoroki, and Suzuki, 2015). In order to detect delamination in the specimen, an induction heating was initiated to increase the temperature of the specimen. The damaged area was identified based on the gradients of temperature across the specimen. Since delamination increases the temperature of a composite laminate, the spots with higher temperature indicate the defective locations (Mizukami, Mizutani, Todoroki, and Suzuki, 2015). The induction heating improved the effectiveness of the eddy-current testing for the detection of delamination in the laminate. According to the authors, the IHAET can detect delamination faster than ultrasonic testing because it does not require scanning time and a coupling medium. (Mizukami, Mizutani, Todoroki, and Suzuki, 2015) used a statistical diagnosis method (Suzuki, Todoroki, Mizutani, and Matsuzaki, 2011) known as system identification-F test method (SI-F method) and IHAET sensors to detect a 2mm deep delamination with an area of 450 mm^2 in a 4mm thick specimen. However, the method could not detect a delamination as large as 300 mm^2.

3.3.3 Electrical Resistance

Among other features, carbon fibres have high electrical conductivity. With this property, carbon fibres are capable of conducting electricity in CFRPs. The presence of damage in the CFRPs may alter the electrical conductivity of the carbon fibres, due to, for example, the discontinuity of the fibres. Hence, the fibres in the CFRPs may act as embedded sensors (Abry, Choi, Chateauminois, Dalloz, Giraud, and Salvia, 2001; Kupke, Schulte, and Schüler, 2001; Wen, Xia, and Choy, 2011) that can be used for SHM (De Baere, Van Paepegem, and Degrieck, 2010).

In 1999, Abry, Bochard, Chateauminois, Salvia, and Giraud (1999) conducted a two-stage study on CFRPs: the inspection of the route of electrical conduction in an unloaded test specimen based on the change of electrode location, and the implementation of monotonic (tension and compression) and cyclic testing of CFRPs of different fibre fractions. The authors observed that the path of electrical conductivity across the CFRPs occurred in the longitudinal direction of the fibre and in the transverse direction of the plies. The presence of damage in the composite laminate reduced the level of electrical conductivity. The advantage of this method is that it can be used to detect very small damage in terms of fibre breakage. However, the accuracy of this method depends on how large the through-thickness resistivity of the fibres is. This implies that the volume of the fibres and location of electrodes will determine the level of sensitivity of this method to the presence of damage.

Wang, Chung, and Chung (2005) monitored the impact damage on continuous carbon fibre epoxy-matrix composite laminates by measuring the electrical resistance. Their work was aimed at verifying the possibility of detecting impact damage on carbon fibre epoxy-matrix composite laminates, examining the capability of the oblique and surface resistances for damage detection in the test composites, and the comparison between the effectiveness of ultrasonic and electrical resistance measurement techniques. From the results, it was noticed that the surface resistance is sensitive to fibre breakage and the oblique resistance is more sensitive to delamination of the fibre. This technique is claimed to be more sensitive to damage in carbon fibre composites than ultrasonic techniques are (Wang, Chung, and Chung, 2005).

Viets, Kaysser, and Schulte (2014) used electrical resistance measurements for the identification of BVIDs in GFRPs that are altered with nanoparticles. They studied the effect of diverse nanoparticles and filler contents. The determination of the local electrical resistance changes due to the presence of impact damage introduced on the specimen with an impact of 7.65J was aided with silver ink electrodes on the test specimen. It was stated that this technique is suitable for both on-site and off-site SHM of FRP structures.

Kwon, Wang, Choi, Shin, Devries, and Park (2016) examined the level of sensitivity of CNT paste to damage in composites using electrical resistance measurements. The dispersion of the CNT in the epoxy matrices was inspected using electrical resistance measurements and its load-sensing ability during tensile testing was observed by four point electrical resistance measurements. Artificial cracks were introduced into the test specimens and the cracks were filled with CNT paste (Kwon, Wang, Choi, Shin, Devries, and Park, 2016). The variation in the electrical resistance of the test specimen was used to detect cracks progression.

3.3.4 Infrared Thermography

Infrared thermography is highly suitable for the monitoring and detection of porosity in composite laminates. The pore morphology of composite materials is of great concern in the aerospace industry (Mayr, Plank, Sekelja, and Hendorfer, 2011) since the porosity of the material reduces the mechanical properties of the composite laminates. This could compromise the safety of the structure. Due to the increasing application of CFRPs in the manufacturing of critical parts of aeronautical structures, it is important to continuously monitor and detect any inherent fault in it promptly.

The porosity in the composite normally occurs during the curing procedure due to loss of pressure in the autoclave (Mayr, Plank, Sekelja, and Hendorfer, 2011). Therefore, effective quality control and inspection methods should be put in place during production to detect possible voids at the earliest stage. Mayr, Plank, Sekelja, and Hendorfer (2011) assessed the porosity in CFRPs using active thermography. In their work, X-ray computed tomography was used to determine the level of porosity and the microstructure of the pores. From the results obtained, it was observed that the shape and size of the pores in the composite affects the measured thermal diffusivity. In addition, the experimental result on active thermography correlates with the results obtained by an ultrasonic method with respect to the influence of the shapes of pores.

Meola and Toscano (2014) explored the use of flash thermography to determine the quantity and distribution of pores in composite laminates. They presented relevant literature with respect to the use of flash thermography to assess the percentage of porosity in fibre reinforced composite materials. In their experiment, new data were obtained from some specimens, which has a different level of porosity, two different stacking sequences, and insertion of slags in the specimen in order to simulate local delamination. It was confirmed that the measure of thermal diffusivity using flash thermography as a porosity evaluation parameter, is a substitute to the ultrasonic attenuation estimation. The use of flash thermography requires no coupling media, surface finishing does not affect its use, it can detect defects and assess the level of porosity within one test (Meola and Toscano, 2014).

Meola and Carlomagno (2010) used infrared thermography to study the effect of low-velocity impact on GFRPs. Their work has two objectives: the mapping of the temperature of the surface of the specimen when impacted and non-destructive evaluation (NDE) before and after impact on the specimen. An optical lock-in thermography was used to inspect the test specimen for possible manufacturing defects. The different energy level was impacted on the specimen and the material behaviour was monitored with an infrared camera. The results obtained indicates that during impact there were variations in temperature within a short time and only high-frequency imaging device was able to capture it. The initiation of damage can be determined from the temperature-time maps. In fact, the increase in temperature corresponds to the onset of the impact damage on the specimen.

Defects in the bond due to delamination, the wrong installation of CFRP to concrete, and cracking can impact on the integrity of the composite CFRP system (Tashan and Al-mahaidi, 2012). Infrared thermography testing method has been reliable in detecting and monitoring of bond defects in composite materials (Tashan and Al-mahaidi, 2012). Tashan and Al-mahaidi (2012) used active pulse thermography and lock-in thermography to investigate bond defects between layers of CFRP laminates in concrete and CFRP fabric in steel. The active pulse thermography works based on exposing the surface of the test material short temperature stimulation and recording the temperature pattern of the heated test material as thermal images, while the lock-in thermography generates heat externally same way as the pulsing procedure but covers a broader range of different thermal frequencies (Tashan and Al-mahaidi, 2012). The results from their experiment indicate that the maximum thermal magnitude has a linear relationship with the input heat flux. In addition, the number of CFRP layers determines how accurate infrared thermography can detect the sizes and shapes of possible defects. The smaller the layers the more accurate the detection. The capability of this technique also depends on the heating method, positioning, and the inspection intervals.

Montanini and Freni (2012) simulated subsurface defects in glass fibre reinforced plastic laminates used for the manufacturing of yachts. They used an optically excited lock-in thermography to quantitatively assess defects in it. The authors assessed the influence of the defect aspect ratio, detectability of defects simulating delamination, and the influence of damages over the gel-coat finish layer. The results show that lock-in infrared thermography is very efficient for the detection of defects in GFRP structures. However, some limitations were evident when used to inspect thick GFRP marine structures, due to inhomogeneity, high thermal transmittance, and a low emissivity of the gel-coated surface. This makes it difficult to measure the radiation and flaw sizing. In addition, Maier, Schmidt, Oswald-Tranta, and Schledjewski (2014) study the capacity of infrared thermography to detect low impact damages in composite plates. The aim of their work was to detect the impact damaged locations and provide information on its location for more damage analysis. They charged the test specimens with specified impact loads to simulate the effect of stone chips and analysed the specimens with thermography. From the results, it was shown that impact events were elastic for lower impact energies that are up to 3J. In addition, at impact energies up to 4J, it was possible to detect the damage by visual inspection. While impact energies up to 5J and beyond will result in catastrophic damage, making it very easy to detect visually.

3.3.5 Nonlinear Elastic Wave Spectroscopy

The nonlinear elastic wave characteristics are able to indicate early signs of degradation on a material (Van Den Abeele, Johnson and Sutin, 2000). Among other researchers, Meo and Zumpano,(2005) studied the suitability of nonlinear elastic wave spectroscopy (NEWS) in the detection of impact damage in a sandwich panel. This technique detects damages from the presence of harmonics and sidebands on the spectrum of the acquired signal. These are generated by the high and low-frequency harmonic signal interaction (Zumpano and Meo, 2008a). In their study, they generated a high-frequency signal and a low-frequency signal with two distinct PZTs. Three acoustic sensors were used to collect the response signals for analysis. The experiment was conducted on damaged and undamaged specimens for comparison. From the analysis, the nonlinearity of the damaged specimen showed sidebands and harmonics of the excited frequencies. However, the NEWS technique cannot indicate the location of damage, but its presence alone.

Zumpano and Meo (2008b) presented a transient nonlinear elastic wave spectroscopy (TNEWS) to detect and localise damage in a composite panel. The TNEWS measures the variations in the transient dynamic responses of a structure based on its nonlinear behaviour caused by damage. The TNEWS detects damage in a three-staged process: acquisition of the structural responses, detection of damage, and the localisation of damage (Zumpano and Meo, 2008b). The authors were able to detect and localise damage in the test specimen with this technique.

3.4 Artificial Neural Networks

Artificial neural networks (ANN) SHM based methods appeared as a result of the possible presence of multi-variant damages in a particular structure (Montalvao, Maia, and Ribeiro, 2006). ANN is an approach that is capable of learning when trained and this characteristic has made it useful in SHM and other engineering applications. The training procedure ends when the mean-square-error between the observed data and the ANN results for the entire element has reached a specified target or after the completion of a specified learning period (El Kadi and Al-Assaf, 2002b). It is an adaptive structure that changes its architecture or input information that passes through the network during the training phase (Sheela and Deepa, 2013). It processes input information, just as the brain does (Sahin, and Shenoi, 2003). With the correct inputs, ANN enables detecting faults and predicting the remaining useful life of materials and structures. ANN consists of layers of input nodes or neurons, one or more hidden neurons, and output layers of neurons. The hidden neurons are between the input and output neurons (El Kadi, 2006). The two classes of ANN are feed-forward network and feedback network (Sheela and Deepa, 2013). The advantages of the ANN technique are that it offers a processing speed and can process multiple inputs (Watkins, Akhavan, Dua, Chandrashekhara, and Wunsch, 2007). In fact, the ANN can also be used to segment radiographic images of damage in composite laminates for evaluation (De Albuquerque, Tavares, and Durao, 2010)

El Kadi and Al-Assaf (2002a) used the strain energy as the input to a modular neural network (MNN) to determine the fatigue life of a composite material. They used the MNN model in order to reduce pattern interference that could result from various inputs, including maximum stress, stress ratio, and fibre orientation. Fatigue tests of 2 million cycles were conducted on unidirectional fibre reinforced composite laminates using a servo-hydraulic testing machine. A 10% reduction in the elastic modulus for the specimens with 0° orientation was defined as a failure (El Kadi and Al-Assaf, 2002a). They compared the result from the MNN model, with strain energy as input, and the one from ANN, with stress ratio, maximum stress applied, and the orientation angle as inputs. The results indicated that strain energy can be used as a valid sole input parameter to the neural network in order to predict fatigue failure in unidirectional composite materials.

Yam, Yan, and Jiang (2003) integrated vibration responses, wavelet transforms and ANN models. This was done through numerical simulations and experimental analysis. In their study, a piezoelectric patch actuator and sensors were used to excite and acquire the structural responses. The wavelet energy spectrum of the decomposed structural vibration responses was used to acquire the features of damage in the structure and an ANN was used to classify and detect damage. The results confirmed the suitability of ANN for detection, location, and classification of damage in composite structures. In addition, they were able to establish mapping relationships between the location and severity of damage and the damage feature of the structure.

Sahin and Shenoi (2003) utilised global (changes in natural frequencies) and local (curvature mode shapes) vibration-based inputs for ANNs to identify and predict the criticality of damage in fibre-reinforced plastic (FRPs) laminates. They obtained the dynamic characteristics of an undamaged and damaged cantilever composite beam for the first three natural modes using finite element analysis. In their work, the damage was initiated in six different locations along the length of the beam. To train the ANNs for the analysis, a different mix of input data from the first three natural modes of the beam was introduced (Sahin and Shenoi, 2003). They used a variety of stiffness reductions at the different locations along the composite beam to generate 126 damage scenarios. The results obtained indicated that there is a correlation between the chosen features that are used as input data and the correct identification of damage.

Watkins, Akhavan, Dua, Chandrashekhara, and Wunsch (2007) used ANNs to outline damages caused by impacts on the composite plate. The type of damage and its severity were linked to the strain signals emitted from the impact on the composite plate. They observed that the impacts that caused damage had a higher peak strain and a more orderly strain profile than that of non-damaging impacts.

Just-Agosto, Serrano, Shafiq, and Cecchini (2008) combined vibration and thermal signals to detect and characterise damage in a sandwich composite material using ANN. They studied the response to various damages in the structure using the transient temperature response (Shilbayeh, and Iskandarani, 2004) and mode shape curvature (Doebling, Farrar, Prime, and Shevitz, 1996) methods. A numerical analysis was conducted with finite element and finite volume methods. The data collected from the numerical simulations was used to train the neural network. The results they got indicated that the combination of vibration and thermal signatures with the neural network were effective in detecting damage, identifying the type, its location and severity (Just-Agosto, Serrano, Shafiq, and Cecchini, 2008).

A vibration-based method with ANN was recently used to establish the fibre volume fraction in GFRP (Farhana, Majid, Paulraj, Ahmadhilmi, Fakhzan, and Gibson, 2016). The fibre volume fraction has a direct effect on the mechanical properties of a composite material. Therefore, this could be used for quality control purposes, for example. In this study, experimental protocols were developed in order to acquire the pattern of vibration. They also developed an autoregressive model to classify the fibre volume fractions and a pole-tracking algorithm to establish the positions of the autoregressive pole. It is from the common knowledge that the higher the fibre volume fraction, the higher the stiffness and the strength of a composite material. However, when the fibre volume fraction exceeds a certain amount, it may actually reduce the ultimate strength of the composite laminate (Farhana, Majid, Paulraj, Ahmadhilmi, Fakhzan, and Gibson, 2016). The proposed method by Farhana, Majid, Paulraj, Ahmadhilmi, Fakhzan, and Gibson (2016) is only suitable for unidirectional GFRP.

Jiang, Zhang, and Friedrich (2007) used the composition of the composite material and testing conditions as inputs and mechanical properties (compressive modulus, tensile strength, compressive strength, flexural strength, specific wear rate and frictional coefficient) as output parameters of the ANN. The result showed that the ANN was able to predict the output parameters based on the input parameters accurately, the reason why the proposed technique is offered as a possible approach for SHM. However, the effectiveness of the ANN depends largely on the robustness of the experimental database for the network training (Jiang, Zhang, and Friedrich, 2007). The larger the database, the more accurate its damage predictability. Unfortunately, it is not always easy (or even possible) to get such a large set of data in real time.

Finally, a comprehensive summary various damage identification technique and their applications are presented in Table 1. The information can be used as a quick reference to engineers and scientist involved in SHM.

4 Prognosis

The prognosis is the last level among the four steps of classification of damage detection methods presented by (Rytter, 1993). It is the prediction of the remaining life cycle of a system when a fault has been already present, which is of high importance to several industries. Prognosis saves resources, eliminates unplanned breakdown of facilities, and provides a window for maintenance activities or replacement of equipment. Hence, this area of damage detection has recently received considerable attention from researchers. Due to its feed forward, predictive and unique nature, it is a topic that deserves to be a science on its own.

For example, Surace and Worden (2011) proposed an approach to damage prognosis that takes into consideration the consequences of uncertainties. It is based on integrating the damage progression laws within the framework of interval arithmetic. In interval arithmetic, each quantity is represented as an interval of possibilities ranging between upper and lower boundary values. They considered two case studies for the approach: the first case study considers an isotropic finite plate that is under harmonic uniaxial loading. A central mode I through-crack damage was introduced. They assumed the Paris-Erdogan law for the damage propagation model. The second case study considers internal delamination growth in composite plates that is under cyclic compression. In their work, the crack/delamination length was considered as the interval quantity and the remaining life of the crisp is defined in terms of the point when the upper boundary on the length exceeds a specified threshold. Then, the lower boundary becomes the safe-life of the structure. According to the authors, the number of cycles can also be considered as an interval quantity and the safe-life of the structure can be determined in terms of the lower boundary of the lifetime when the length of the crisp crack/delamination exceeds the specified point.

Furthermore, Peng, Liu, Saxena, and Goebel (2015) proposed a prognosis framework for a real-time composite fatigue life. The methodology of the prognosis combines sensor measurements, Bayesian inference, and a mechanical stiffness degradation model for the prediction of real-time fatigue life. They used open-hole test specimen data sets to establish and validate the proposed method. The authors finally used a prognostic metric to evaluate the predictions of the proposed model. Among several conclusions drawn from their results, the remaining life of the test specimen is small when the stiffness is below 0.75 of the stiffness of the undamaged specimen.

Finally, a summary of the techniques applied to damage detection in composite structures are stated in Tab. 4.1. The table provides an overview of the area of application of different techniques, their advantages and limitations.

Table 4.1: Summary of the Damage Techniques

Techniques	Advantages	Limitations	Ranges of Application	Rytter's Scale	Types of damage detected in composites
Vibration-based techniques	Easy to implement; Cost-effective; High sensitivity to damage.	Non-unique solutions; Errors in measurements; Environmental factors.	Aerospace industries; Automobile industries; Inspection of civil infrastructure.	Stage I, II, III, and IV	Delamination; Cracks.
Transmissibility	Simple to implement; Sensitive to local changes in structures; Uses only the output response; Does not need the operational forces be white noise; Can be a swept sine, coloured noise, or impact.	Difficult to apply without supervision.	Civil engineering; Marine industries (determination of Ship mechanical noise); Automobile industries (applied to data from a real vehicle); Health monitoring in composite structures.	Stage I, II, and III	Delamination; Debonding.
Damping	Sensitive to small cracks; Sensitive to variations in structural stiffness.	Numerous definitions; Errors involved in finding the values of damping; Difficult to model analytically.	Civil engineering; Aeronautic industries; Automobile industries; Health monitoring in composite structures.	Stage I, II, III, and IV	Cracks; Delamination; Debonding; Fibre fracture; Kink bands; Micro-buckling.

Lamb Waves	Travels over long distances in structure without deviating; Monitor large area from a single point of application; Cost-effective; Can detect internal damages in thin material; High flexibility; Safe, and no harmful radiation; Can inspect parts; Suitable for remote inspection.	Dispersive nature complicates its application; Multiple waveforms in single frequency affect its application; Cannot detect small damages (e.g. localised pitting); Requires skilled personnel for interpretation; No existing standards to work with.	Aerospace industries; Automotive industries; Audio and acoustics data storage; Production testing; Structural testing; Scientific and medical; Ultrasonic; Pipeline inspection; Bridge cable inspection; Rail defect detection; Gas cylinder inspection; Health monitoring in composite structures.	Stage I and II	Cracks; Delamination; Matrix cracking; Broken fibre; Impacts; Adhesive defects on stiffness; Porosity.

Acoustic Emission	Can detect several types damages caused by fatigue loading; High sensitivity; Permanent installation of sensor for process control; Fast results and global monitoring using multiple sensors; Used for leak detection and location; Suitable for proof testing; In-process weld monitoring; Online monitoring; Less intrusive; Remote scanning; Real-time evaluation.	Cannot characterise damage; Difficult to find damage; Requires load application to generate AE event; Requires skilled personnel to correlate data to the specific damage mechanism; Attenuation (the test specimen can attenuate the AE stress wave); A crack that is not propagating cannot be detected.	Civil engineering; Automobile industries; NDT testing; Machining; Aerospace industries; Health monitoring in composite structures.	Stage I, II, and IV	Translaminar cracks; Fibre breakage; Delamination; Fibre matrix debonding; Matrix micro-cracks
Ultrasonic Inspection	Easy to interpret; Can detect early stage of damage initiation; Enhanced sensitivity; Cheap, and readily available.	Limited in depth because of attenuation; Low contrast due to high attenuation and scattering in composites; Variations in composite properties affects its performance.	Aerospace industries; Material research; Quality assurance; Bridges; Monitoring of weld; Gas trailer tubes; Health monitoring in composite structures.	Stage I, II and III	Cracks; Delamination; Debonding.

Acousto-Ultrasonic	Assessment of non-critical damages; A good indicator of accumulated damage due to impact damage.	Not useful for the detection of delamination or voids; Mandatory setup and pre-calculations before testing; Surface roughness and texture affect its performance.	Quality control and assessment of damage in composite materials; Automobile industries; Aeronautic industries; SHM in composite structures.	Stage I, II, III, and IV	Translaminar cracks; Debonding.
Vibro-Acoustic	Sensitive to nonlinearities; Sensitive to cracks; Changes in environmental and loading conditions have negligible effect.	Selection of probe and excitation frequencies needs experienced personnel; The position of clamp with respect to the location of transducer affects the result.	Aeronautic industries; Health monitoring in composite structures; Civil structures; Space industry.	Stage I, II, III, and IV	Fatigue cracks; Delamination; Debonding.
Instrumentation	Can check the damage initiation and evolution; Cost-effective; High precision and sensitivity; Requires little human effort and a limited number of sensors.	Add excess weight to the structure; Affects the stiffness and strength of the material.	Civil infrastructure; Manufacturing industries; Automobile industries; Aerospace industries; Petroleum industries; Pipelines inspection; Nuclear installations; Tunnels; SHM in composite structures.	Stage I, II, III, and IV	Cracks; Delamination; Debonding; Matrix fracture; Surface roughness.
Eddy Currents	Convenient to apply; No contact needed.	Only effective in electro-conductive graphite fibre composites; The sensitivity of the search coil decreases as the lift-off and tilting of the probe increases.	Health monitoring in composite structures.	Stage I, II, III, and IV	Cracks; Delamination; Porosity.

Electrical Resistance Measurement	Sensitive to small damages; Cost-effective; Suitable for both on-site and off-site monitoring of FRP structures.	Its sensitivity depends on the fibre volume and the location of the electrodes.	Civil engineering; Health monitoring in composite structures.	Stage I and II	Fibre fracture; Fibre pullout; Delamination; Debonding; Cracks.
Infrared Thermography	Enables remote sensing; Rapid coverage of large area; Relatively easy to use; Can figure out the exact location of damage; Offers a visual picture of health of a structure; Non-contact.	Generates varying thermal properties in different orientations due to anisotropy; Requires sensitive and expensive instrumentation; Difficult to detect damage that are not close to the surface of the structure.	Research and development; Medicine; Predictive maintenance; Inspection of civil structures; Process optimisation; Observation and investigation; Quality control; Roof surveys; NDT testing; SHM in composite structures.	State I and II	Translaminar cracks in GFRP composites; Foreign inclusions; Impact damage; Voids and cracks in CFRP laminates; Delamination; Accumulation of water in composite sandwich panels; Debonding; Fatigue.
Nonlinear Elastic Wave Spectroscopy	Determination of the thickness of thin test specimen; Detection of damage initiation in both metals and composites; Detection of accumulated damage; Characterisation of structure related properties.	Several effects such as dislocations, micro-cracks lead to various kinds of nonlinearity; Difficult to define reference samples for scattered damage; Amplitude determines the nonlinear effect.	Health monitoring in composite structures; Aerospace structures.	Stage I, II, III, and IV	Porosity; Matrix properties; Delamination; Cracks; Debonding; Fracture; Thermal damage; Corrosion.

Artificial Neural Networks	Can mimic a structure (adaptive learning); High processing speed and can process multiple inputs; Can be used to segment radiographic images of damage in composite laminates; Real-time operation; Handle noisy data.	Skilled personnel required; Large database needed for more accurate damage prediction – but it is difficult to get large data in real-time; Complex solutions consume a lot of time.	Civil structures; Character recognition; Stock market prediction; Medicine; Security (features of fingerprints and fingerprint recognition system); Robotics; Environmental science, Chemical technology, science, and nanotechnology; SHM in composite structures.	Stage I, II, III, and IV	Fatigue; Fibre fracture

5 Conclusion

An updated review of the failure mechanisms in composite structures and non-destructive SHM testing techniques was presented. Despite the excellent mechanical properties of composite materials, they are susceptible to impact damage that can result in unexpected and catastrophic failures. Hence, early damage detection and localization in composite materials is of utmost importance in order to avert downtime and human risks.

Although several methods for damage detection and localization have been developed, they all have their own advantages, limitations, and scope of application. Also, one challenge is related to damage size, which makes it difficult to detect until a certain minimum dimension is attained. However, the quantification of damage and the prediction of the structure's lifetime (prognosis) still are the most complex areas.

Most techniques are based on a comparison between undamaged and damaged states of the materials. A deviation from the data of the undamaged material indicates the presence of damage. Therefore, the health status of the undamaged material must first be established and used as a reference.

Currently, the use of embedded sensors in composite materials is trending: composites are becoming smart materials. This technique enables the material to act as a self-sensor by detecting and localising damage in real time. However, the integrated sensors add weight to the structure and change its mechanical properties. Furthermore, these materials must be manufactured with the sensors beforehand. Therefore, for composite structures that do not have embedded sensors, other

SHM frameworks must be chosen, depending on many several factors that were illustrated throughout this paper.

Many of the techniques are based on changes in the structural dynamic response, which includes changes in the modal properties (natural frequencies, damping modal factors and mode shapes). For composite materials, damping appears to be a suitable candidate to be used as a damage sensitive feature. This is because there is a correlation between damping and the energy dissipated on the composite material during vibration. It is noteworthy to mention that the natural frequencies can also provide information about the presence of damage, as this is usually related to a reduction in stiffness, but it is the combination of different parameters what usually makes a more robust method. Finally, the assessment of nonlinearities, especially due to delamination, has also shown to be a promising technique to detect damage.

Nevertheless, experimental uncertainties still are the greatest hindrance to most methods, reason why no method truly is false-negative or false-positive free. This can happen when factors such as an increase in temperature, changes in mass due to the installation of sensors and stiffness variations introduce more differences than damage itself. Uncertainty is the one primary limitation of structural damage detection and characterisation.

Based on the many papers reviewed, researchers have been more focused on flat composite plates reinforced with synthetic fibres. There are relatively fewer works on more complex structural geometries, hybrid reinforced composites and natural fibre reinforced composites. It would be interesting to assess how the available techniques would perform with more complex designs.

6 References

Abrate, S. (1994). Impact on Laminated Composites: Recent Advances. *Applied Mechanics Reviews*, *47*(January 1994), 517.

Abry, J. C., Bochard, S., Chateauminois, A., Salvia, M., & Giraud, G. (1999). In situ detection of damage in CFRP laminates by electrical resistance measurements. *Composites Science and Technology*, *59*(6), 925–935.

Abry, J. C., Choi, Y. K., Chateauminois, A., Dalloz, B., Giraud, G., & Salvia, M. (2001). In-situ monitoring of damage in CFRP laminates by means of AC and DC measurements. *Composites Science and Technology*, *61*(6), 855–864.

Aggelis, D. G., Barkoula, N. M., Matikas, T. E., & Paipetis, A. S. (2012). Acoustic structural health monitoring of composite materials : Damage identification and evaluation in cross ply laminates using acoustic emission and ultrasonics. *Composites Science and Technology*, *72*(10), 1127–1133.

Akil, H. M., De Rosa, I. M., Santulli, C., & Sarasini, F. (2010). Flexural behaviour of pultruded jute/glass and kenaf/glass hybrid composites monitored using acoustic emission. *Materials Science and Engineering A*, *527*(12), 2942–2950.

Alexandrov, S., Erisov, Y., & Grechnikov, F. (2016). Effect of the Yield Criterion of Matrix on the Brittle Fracture of Fibres in Uniaxial Tension of Composites. *Advances in Materials Science and Engineering*, *2016*(April 28).

Alexopoulos, N. ., Bartholome, C., Poulin, P., & Marioli-Riga, Z. (2010). Structural health monitoring of glass fiber reinforced composites using embedded carbon nanotube (ENT) fibres. *Composites Science and Technology*, *70*(2), 260–271.

Argüelles, A., Viña, J., Canteli, A. F., and Bonhomme, J. (2010). Fatigue delamination, initiation,

and growth, under mode I and II of fracture in a carbon‐ fiber epoxy composite. *Polymer Composite*, *31*(4), 700–706.
Aymerich, F., & Meili, S. (2000). Ultrasonic evaluation of matrix damage in impacted composite laminates. *Composites Part B: Engineering*, *31*(1), 1–6.
Aymerich, F., & Staszewski, W. J. (2010a). Experimental Study of Impact-Damage Detection in Composite Laminates using a Cross-Modulation Vibro-Acoustic Technique. *Structural Health Monitoring*, *9*(6), 541–553.
Aymerich, F., & Staszewski, W. J. (2010b). Impact damage detection in composite laminates using nonlinear acoustics. *Composites Part A: Applied Science and Manufacturing*, *41*(9), 1084–1092.
Bai, J., and Phoenix, S. L. (2005). Compressive failure model for fiber composites by kink band initiation from obliquely aligned, shear-dislocated fiber breaks. *International Journal of Solids and Structures*, *42*(7), 2089–2128.
Baran, I., Tutum, C. C., Nielsen, M. W., & Hattel, J. H. (2013). Process induced residual stresses and distortions in pultrusion. *Composites Part B: Engineering*, *51*(August 31), 148–161.
Barbezat, M., Brunner, a. J., Huber, C., & Flueler, P. (2007). Integrated Active Fiber Composite Elements: Characterization for Acoustic Emission and Acousto-ultrasonics. *Journal of Intelligent Material Systems and Structures*, *18*(May), 515–525.
Barbieri, E., and Meo, M. (2009). A meshfree penalty-based approach to delamination in composites. *Composites Science and Technology*, *69*(13), 2169–2177.
Bazant, Z. P., Kim, J.-J. H., Daniel, I. M., Becq-Giraudon, E., & Zi, G. (1999). Size Effect on Compression Strength of Fiber Composites Failing by Kink Band Propagation. *International Journal of Fracture*, *95*(Bažant 1984), 103–141.
Bedsole, R. W., Bogert, P. B., & Tippur, H. V. (2015). An experimental investigation of interlaminar and intralaminar dynamic fracture of CFRPs: Effect of matrix modification using carbon nanotubes. *Composite Structures*, *132*, 1043–1055.
Ben, B. S., Ben, B. A., Vikram, K. A., & Yang, S. H. (2013). Damage identification in composite materials using ultrasonic based Lamb wave method. *Measurement*, *46*(2), 904–912.
Berbinau, P., Soutis, C., & Guz, I. A. (1999). Compressive failure of 0° unidirectional carbon-fibre-reinforced plastic (CFRP) laminates by fibre microbuckling. *Composites Science and Technology*, *59*(9), 1451–1455.
Blom, J., El Kadi, M., Wastiels, J., & Aggelis, D. G. (2014). Bending fracture of textile reinforced cement laminates monitored by acoustic emission: Influence of aspect ratio. *Construction and Building Materials*, *70*, 370–378.
Blom, J., Wastiels, J., & Aggelis, D. G. (2014). Application of acoustic emission on the characterization of fracture in textile reinforced cement laminates. *The Scientific World Journal*, *2014*.
Bobrov, A., & Stepanova, L. (2013). Studying the parameters of acoustic emission signals during inspection of cast parts of a freight car truck. *Russian Journal of Nondestructive Testing*, *49*(12), 722–727.
Bonavolonta, C., Valentino, M., Marrocco, N., & Pepe, G. P. (2009). Eddy current technique based on-SQUID and GMR sensors for non-destructive evaluation of fiber/metal laminates. *IEEE Transactions on Applied Superconductivity*, *19*(3), 808–811.
Bonavolontà, C., Valentino, M., Pepe, G. P., & Bonavolontà, C., Valentino, M. and Pepe, G. . (2007). Characterization of the damage process in GLARE 2 using an eddy current technique based on HTS-SQUID magnetometer. *Superconductor Science and Technology*, *20*(1), 51–56.
Bravo, A., Toubal, L., Koffi, D., & Erchiqui, F. (2015). Damage Characterization of Bio and Green Polyethylene–Birch Composites under Creep and Cyclic Testing with Multivariable Acoustic Emissions. *Materials*, *8*(11), 7322–7341.

Budiansky, B., Fleck, N. A., and Amazigo, J. C. (1998). On kink-band propagation in fiber composites. *Journal of the Mechanics and Physics of Solids*, *46*(9), 1637–1653.

Cantwell, W. J., & Morton, J. (1989). Comparison of the low and high velocity impact response of CFRP. *Composites*, *20*(6), 545–551.

Carboni, M., Gianneo, A., & Giglio, M. (2015). A Lamb waves based statistical approach to structural health monitoring of carbon fibre reinforced polymer composites. *Ultrasonics*, *60*, 51–64.

Carlone, P., Baran, I., Hattel, J. H., & Palazzo, G. S. (2013). Computational approaches for modeling the multiphysics in pultrusion process. *Advances in Mechanical Engineering*, *2013*(5), 301875.

Carpinteri, A., Lacidogna, G., Accornero, F., Mpalaskas, A. ., Matikas, T. E., & Aggelis, D. G. (2013). Influence of damage in the acoustic emission parameters. *Cement and Concrete Composites*, *44*, 9–16.

Cawley, P., & Alleyne, D. (1996). The use of Lamb waves for the long range inspection of large structures. *Ultrasonics*, *34*(2–5), 287–290.

Cenek, S., Mudit, R., & Radek, H. (2014). Structural Health Monitoring of Composite Structures using embedded PZT Sensors in Space Application. In *In The 2nd European conference of the prognostics and health management society*.

Chandra, N., and Ghonem, H. (2001). Interfacial mechanics of push-out tests: theory and experiments. *Applied Science and Manufacturing*, *32*(3), 575–584.

Chrysochoidis, N. A., Barouni, A. K., & Saravanos, D. A. (2011). Delamination detection in composites using wave modulation spectroscopy with a novel active nonlinear acousto-ultrasonic piezoelectric sensor. *Journal of Intelligent Material Systems and Structures*, *22*(18), 2193–2206.

Craven, R., Pindoria, S., & Olsson, R. (2009). Finite element study of compressively loaded fibres fractured during impact. *Composites Science and Technology*, *69*(5), 586–593.

Davidson, P., & Waas, A. . (2012). Non-smooth mode I fracture of fibre-reinforced composites: an experimental, numerical and analytical study. Philosophical Transactions of the Royal Society of London A. *Mathematical, Physical and Engineering Sciences*, *370*(1965), 1942–1965.

De Albuquerque, V. H. C., Tavares, J. M. R., & Durao, L. M. (2010). Evaluation of Delamination Damage on Composite Plates using an Artificial Neural Network for the Radiographic Image Analysis. *Journal of Composite Materials*, *44*(9), 1139–1159.

De Baere, I., Van Paepegem, W., & Degrieck, J. (2010). Electrical resistance measurement for in situ monitoring of fatigue of carbon fabric composites. *International Journal of Fatigue*, *32*(1), 197–207.

Devriendt, C., & Guillaume, P. (2007). The use of transmissibility measurements in output-only modal analysis. *Mechanical Systems and Signal Processing*, *21*(7), 2689–2696.

Devriendt, C., & Guillaume, P. (2008). Identification of modal parameters from transmissibility measurements. *Journal of Sound and Vibration*, *314*(1–2), 343–356.

Devriendt, C., Presezniak, F., De Sitter, G., Vanbrabant, K., De Troyer, T., Vanlanduit, S., & Guillaume, P. (2010). Structural health monitoring in changing operational conditions using tranmissibility measurements. *Shock and Vibration*, *17*(4–5), 651–675.

Dhieb, H., Buijnsters, J.G., Elleuch, K. and Celis, J. . (2016). Effect of relative humidity and full immersion in water on friction, wear and debonding of unidirectional carbon fibre reinforced epoxy under reciprocating sliding. *Composites Part B: Engineering*, *88*, 240–252.

Diamanti, K., Soutis, C., & Hodgkinson, J. M. (2005). Lamb waves for the non-destructive inspection of monolithic and sandwich composite beams. *Composites Part A: Applied Science and Manufacturing*, *36*(2 SPEC. ISS.), 189–195.

Doebling, S.W., Farrar, C.R., Prime, M.B. and Shevitz, D. W. (1996). Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in Their Vibration

Characteristics: A Literature Review. In *(No. LA--13070-MS). Los Alamos National Lab.*, (pp. 1–136). NM (United States).
Dutta, D., Sohn, H., Harries, K. a., & Rizzo, P. (2009). A Nonlinear Acoustic Technique for Crack Detection in Metallic Structures. *Structural Health Monitoring*, *8*(3), 251–262.
Dziendzikowski, M., Dragan, K., Kurnyta, A., Kornas, Ł., Latoszek, A., Zabłocka, M., … Giewoń, J. (2014). An approach to structural health monitoring of composite structures based on embedded PZT transducers. *Fatigue of Aircraft and Structures*, *2014*(6), 113–118.
El Kadi, H. (2006). Modeling the mechanical behavior of fiber-reinforced polymeric composite materials using artificial neural networks—A review. *Composite Structures*, *73*(1), 1–23.
El Kadi, H., & Al-Assaf, Y. (2002a). Energy-based fatigue life prediction of fiberglass/epoxy composites using modular neural networks. *Composite Structures*, *57*(1), 85–89.
El Kadi, H., & Al-Assaf, Y. (2002b). Prediction of the fatigue life of unidirectional glass fibre/epoxy composite laminate using different neural network paradigms. *Composite Structures*, *55*(2), 239–246.
Farhana, N.I.E., Majid, M. A., Paulraj, M. P., Ahmadhilmi, E., Fakhzan, M. N., & Gibson, A. . (2016). A novel vibration based non-destructive testing for predicting glass fibre/matrix volume fraction in composites using a neural network model. *Composite Structures*, *144*, 96–107.
Fotouhi, M., Suwarta, P., Jalalvand, M., Czel, G., & Wisnom, M. R. (2016). Detection of fibre fracture and ply fragmentation in thin-ply UD carbon/glass hybrid laminates using acoustic emission. *Composites Part A: Applied Science and Manufacturing*, *86*, 66–76.
Gamstedt, E. . (2000). Effects of debonding and fiber strength distribution on fatigue‐ damage propagation in carbon fiber‐ reinforced epoxy. *Journal of Applied Polymer Science*, *95*(7), 716–728.
Gayathri, P., Umesh, K., & Ganguli, R. (2010). Effect of matrix cracking and material uncertainty on composite plates. *Reliability Engineering & System Safety*, *95*(7), 716–728.
Ghezzo, F., Starr, A. F., & Smith, D. R. (2010). Integration of networks of sensors and electronics for structural health monitoring of composite materials. *Advances in Civil Engineering*, *2010*.
Giurgiutiu, V., & Santoni-Bottai, G. (2011). Structural Health Monitoring of Composite Structures with Piezoelectric-Wafer Active Sensors. *AIAA Journal*, *49*(3), 565–581.
Gonilha; J.A., Correia; J.R., F.A., B., E., C., & Cunha; Á. (2013). Modal identification of a GFRP-concrete hybrid footbridge prototype: Experimental tests and analytical and numerical simulations. *Composite Structures*, *106*, 724–733.
Gonzalez‐ Chi, P. I., Flores‐ Johnson, E. A., Carrillo‐ Baeza, J. G., and Young, R. J. (2010). Micromechanical analysis of the kink‐ band performance at the interface of a thermoplastic composite under tensile deformation. *Polymer Composites*, *31*(10), 1817–1821.
Gyekenyesi, A. L., Morscher, G. N., & Cosgriff, L. M. (2006). In situ monitoring of damage in SiC/SiC composites using acousto-ultrasonics. *Composites Part B: Engineering*, *37*(1), 47–53.
Hamdi, S. E., Le Duff, A., Simon, L., Plantier, G., Sourice, A., & Feuilloy, M. (2013). Acoustic emission pattern recognition approach based on Hilbert-Huang transform for structural health monitoring in polymer-composite materials. *Applied Acoustics*, *74*(5), 746–757.
Harich, J., Lapusta, Y., and Wagner, W. (2009). 3D FE-modeling of surface and anisotropy effects during micro-buckling in fiber composites. *Composite Structures*, *89*(4), 551–555.
Hasiotis, T., Badogiannis, E., & Tsouvalis, N. G. (2011). Application of ultrasonic C-scan techniques for tracing defects in laminated composite materials. *Strojniski Vestnik/Journal of Mechanical Engineering*, *57*(3), 192–203.
Henaff-Gardin, C., Lafarie-Frenot, M. ., & Gamby, D. (1996). Doubly periodic matrix cracking in composite laminates Part 2: Thermal biaxial loading. *Composite Structures*, *36*(1), 131–140.
Herb V, Couégnat G, M. E. (2010). Damage assessment of thin SiC/SiC composite plates subjected

to quasi-static indentation loading. *Composites Part A: Applied Science and Manufacturing*, *41*(11), 1677–1685.
Herman, A. P., Orifici, A. C., & Mouritz, A. P. (2013). Vibration modal analysis of defects in composite T-stiffened panels. *Composite Structures*, *104*, 34–42.
Hosur, M. V., Murthy, C. R. L., Ramamurthy, T. S., & Shet, A. (1998). Estimation of impact-induced damage in CFRP laminates through ultrasonic imaging. *NDT & E International*, *31*(5), 359–374.
Hsu, S.-Y., Vogler, T. J., & Kyriakides, S. (1999). On the axial propagation of kink bands in fiber composites : Part II analysis. *International Journal of Solids and Structures*, *36*(4), 575–595.
Hu, N., Liu, Y., Li, Y., Peng, X., & Yan, B. (2010). Optimal Excitation Frequency of Lamb Waves for Delamination Detection in CFRP Laminates. *Journal of Composite Materials*, *44*(13), 1643–1663.
Huang, L., Sheikh, A. H., Ng, C. T., Griffith, M. C. (2015). An efficient finite element model for buckling analysis of grid stiffened Laminated composite plates. *Composite Structures*, *122*, 41–50.
Huang, W., Zhang, W., & Li, F. (2013). Acoustic emission source location using a distributed feedback fiber laser rosette. *Sensors (Basel, Switzerland)*, *13*(10), 14041–14054.
Jen, M. ., & Lee, C. . (1998). Strength and life in thermoplastic composite laminates under static and fatigue loads. Part I: Experimental. *International Journal of Fatigue*, *20*(9), 605–615.
Jia, Y., Chen, Z., and Yan, W. (2014). A numerical study on carbon nanotube–hybridized carbon fibre pullout. *Composites Science and Technology*, *91*, 38–44.
Jiang, Z., Zhang, Z., & Friedrich, F. (2007). Prediction on wear properties of polymer composites with artificial neural networks. *Composites Science and Technology*, *67*(2), 168–176.
Just-Agosto, F., Serrano, D., Shafiq, B., & Cecchini, A. (2008). Neural network based nondestructive evaluation of sandwich composites. *Composites Part B: Engineering*, *39*(1), 217–225.
Kessler, S. S., Spearing, S. M., Atalla, M. J., Cesnik, C. E., & Soutis, C. (2002). Damage detection in composite materials using frequency response methods. *Composites Part B: Engineering*, *33*(1), 87–95.
Kessler, S. S., Spearing, S. M., & Soutis, C. (2002). Damage detection in composite materials using Lamb wave methods. *Smart Materials and Structures*, *11*(2), 269–278.
Keulen, C. J., Yildiz, M., & Suleman, A. (2014). Damage Detection of Composite Plates by Lamb Wave Ultrasonic Tomography with a Sparse Hexagonal Network Using Damage Progression Trends. *Shock and Vibration*, *2014*, 1–8.
Keye, S., Rose, M. and Sachau, D. (2001). Localizing delamination damages in aircraft panels from modal damping parameters. *In Proceedings of the 19th International Modal Analysis Conference (IMAC XIX), Kissimmee*, (Febru), 412–417.
Khandetskii, V. S., & Martynovich, L. Y. (2001). Eddy-Current Nondestructive Detection of Delaminations Near Edges of Composite Materials. *Russian Journal of Nondestructive Testing*, *37*(3), 207–213.
Kim, H. Y. (2003). Vibration-Based Damage Identification Using Reconstructed FRFs in Composite Structures. *Journal of Sound and Vibration*, *259*(5), 1131–1146.
Kim, S., Adams, D. E., Sohn, H., Rodriguez-Rivera, G., Myrent, N., Bond, R., … Meyer, J. J. (2014). Crack detection technique for operating wind turbine blades using Vibro-Acoustic Modulation. *Structural Health Monitoring*, *13*(6), 660–670.
Kinet, D., Mégret, P., Goossen, K. ., Qiu, L., Heider, D., & Caucheteur, C. (2014). Fiber Bragg Grating Sensors toward Structural Health Monitoring in Composite Materials: Challenges and Solutions. *Sensors*, *14*(4), 7394–7419.
Kinra, V. K., Ganpatye, A. S., & Maslov, K. (2006). Ultrasonic Ply-by-Ply Detection of Matrix Cracks in Laminated Composites. *Journal of Nondestructive Evaluation*, *25*(1), 37–49.

Kiral, Z., Içten, B. M., & Kiral, B. G. (2012). Effect of impact failure on the damping characteristics of beam-like composite structures. *Composites Part B: Engineering*, *43*(8), 3053–3060.

Klepka, A., Pieczonka, L., Staszewski, W. J., & Aymerich, F. (2014). Impact damage detection in laminated composites by non-linear vibro-acoustic wave modulations. *Composites Part B: Engineering*, *65*(October 31), 99–108.

Klepka, A., Staszewski, W. J., di Maio, D., & Scarpa, F. (2013). Impact damage detection in composite chiral sandwich panels using nonlinear vibro-acoustic modulations. *Smart Materials and Structures*, *22*(8), 84011.

Ksouri, S., Matmat, M., Boukabache, H., Escriba, C., & Fourniols, J. (2011). Damage detection in composite laminates aeronautics structures through accelerometers network. *Advances in Materials Sciences*, *11*(2), 37–43.

Kupke, M., Schulte, K., & Schüler, R. (2001). Non-destructive testing of FRP by d.c. and a.c. electrical methods. *Composites Science and Technology*, *61*(6), 837–847.

Kwon, D. J., Wang, Z. J., Choi, J. Y., Shin, P. S., Devries, K. L., & Park, J. M. (2016). Damage sensing and fracture detection of CNT paste using electrical resistance measurements. *Composites Part B: Engineering*, *90*, 386–391.

Lamb, H. (1917). On waves in an elastic plate. In The Royal Society (Ed.), *In Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* (Vol. 93, pp. 114–128).

Lang, W., Boll, D., & Schotzko, T. (2012). Function Scale Integration – Embedding Sensors in Materials for Structural Health Monitoring. *6th European Workshop on Structural Health Monitoring*, 1–8.

Lang, Z. Q., & Billings, S. A. (2005). Energy transfer properties of non-linear systems in the frequency domain. *International Journal of Control*, *78*(5), 345–362.

Lang, Z. Q., Park, G., Farrar, C. R., Todd, M. D., Mao, Z., Zhao, L., & Worden, K. (2011). Transmissibility of non-linear output frequency response functions with application in detection and location of damage in MDOF structural systems. *International Journal of Non-Linear Mechanics*, *46*(6), 841–853.

Latifi, M., Van der Meer, F. P., and Sluys, L. J. (2015). A level set model for simulating fatigue-driven delamination in composites. *International Journal of Fatigue*, *80*, 434–442.

Lee, J., and Soutis, C. (2007). A study on the compressive strength of thick carbon fibre–epoxy laminates. *Composites Science and Technology*, *67*(10), 2015–2026.

Lee, K. Il, & Yoon, S. W. (2016). Propagation of time-reversed Lamb waves in acrylic cylindrical tubes as cortical-bone-mimicking phantoms. *Applied Acoustics*, *112*, 10–13.

Li, X. Z., Peng, Z. K., Dong, X. J., Zhang, W. M., & Meng, G. (2015). A New Transmissibility Based Indicator of Local Variation in Structure and Its Application for Damage Detection, *2015*(January 1).

Liu, P. F., Chu, J. K., Liu, Y. L., & Zheng, J. Y. (2012). A study on the failure mechanisms of carbon fiber/epoxy composite laminates using acoustic emission. *Materials & Design*, *37*, 228–235.

Loutas, T. ., Vavouliotis, A., Karapappas, P., & Kostopoulos, V. (2010). Fatigue damage monitoring in carbon fiber reinforced polymers using the acousto-ultrasonics technique. *Polymer Composites*, *31*(8), 1409–1417.

Loutas, T. H., & Kostopoulos, V. (2009a). Health monitoring of carbon/carbon, woven reinforced composites: Damage assessment by using advanced signal processing techniques. Part II: Acousto-ultrasonics monitoring of damage development. *Composites Science and Technology*, *69*(2), 273–283.

Loutas, T. H., & Kostopoulos, V. (2009b). Health monitoring of carbon/carbon, woven reinforced composites. Damage assessment by using advanced signal processing techniques. Part I: Acoustic emission monitoring and damage mechanisms evolution. *Composites Science and Technology*, *69*(2), 265–272.

Lu, S., Jiang, M., Sui, Q., Sai, Y., & Jia, L. (2015). Damage identification system of CFRP using fiber Bragg grating sensors. *Composite Structures*, *125*(July 31), 400–406.

Luo, S., & Liu, T. (2014). Graphite Nanoplatelet Enabled Embeddable Fiber Sensor for in Situ Curing Monitoring and Structural Health Monitoring of Polymeric Composites. *ACS Applied Materials & Interfaces*, *6*(12), 9314–9320.

Maia, N. M. M., Almeida, R. A. B., Urgueira, A. P. V, & Sampaio, R. P. C. (2011). Damage detection and quantification using transmissibility. *Mechanical Systems and Signal Processing*, *25*(7), 2475–2483.

Maia, N. M. M., Ribeiro, A. M. R., Fontul, M., Montalvão, D., & Sampaio, R. P. C. (2007). Using the Detection and Relative Damage Quantification Indicator (DRQ) with Transmissibility. *Key Engineering Materials*, *347*, 455–460.

Maia, N. M. M., & Silva, J. M. M. e. (1997). *Theoretical and Experimental Modal Analysis*. Taunton: Research Studies Press and John Wiley and Sons, Somerset.

Maier, A., Schmidt, R., Oswald-Tranta, B., & Schledjewski, R. (2014). Non-destructive thermography analysis of impact damage on large-scale CFRP automotive parts. *Materials*, *7*(1), 413–429.

Manoach, E., Samborski, S., Mitura, A., & Warminski, J. (2012). Vibration based damage detection in composite beams under temperature variations using Poincaré maps. *International Journal of Mechanical Sciences*, *62*(1), 120–132.

Manson, G., Worden, K., Monnier, T., Guy, P., Pierce, S. G., & Culshaw, B. (2011). Some experimental observations on the detection of composite damage using lamb waves. *Strain*, *47*(Suppl. 1), 254–268.

Mao, Z., & Todd, M. (2012). A model for quantifying uncertainty in the estimation of noise-contaminated measurements of transmissibility. *Mechanical Systems and Signal Processing*, *28*, 470–481.

Masmoudi, S., El Mahi, A., & Turki, S. (2015). Fatigue behaviour and structural health monitoring by acoustic emission of E-glass/epoxy laminates with piezoelectric implant. *Applied Acoustics*.

Mayr, G., Plank, B., Sekelja, J., & Hendorfer, G. (2011). Active thermography as a quantitative method for non-destructive evaluation of porous carbon fiber reinforced polymers. *NDT and E International*, *44*(7), 537–543.

Mba, D., & Rao, R. B. (2006). Development of Acoustic Emission Technology for Condition Monitoring and Diagnosis of Rotating Machines: Bearings, Pumps, Gearboxes, Engines, and Rotating Structures. *The Shock and Vibration Digest*, *38*(1), 3–16.

Mechraoui, S. E., Laksimi, A., & Benmedakhene, S. (2012). Reliability of damage mechanism localisation by acoustic emission on glass/epoxy composite material plate. *Composite Structures*, *94*(5), 1483–1494.

Meo, M., & Zumpano, G. (2005). Nonlinear elastic wave spectroscopy identification of impact damage on a sandwich plate. *Composite Structures*, *71*(3–4), 469–474.

Meola, C., & Carlomagno, G. M. (2010). Impact damage in GFRP: New insights with infrared thermography. *Composites Part A: Applied Science and Manufacturing*, *41*(12), 1839–1847.

Meola, C., & Toscano, C. (2014). Flash thermography to evaluate porosity in carbon fiber reinforced polymer (CFRPs). *Materials*, *7*(3), 1483–1501.

Mizukami, K., Mizutani, Y., Todoroki, A., & Suzuki, Y. (2015). Detection of delamination in thermoplastic CFRP welded zones using induction heating assisted eddy current testing. *NDT & E International*, *74*, 106–111.

Mohammadabadi, M., Daneshmehr, A. R., and Homayounfard, M. (2015). Size-dependent thermal buckling analysis of micro composite laminated beams using modified couple stress theory. *International Journal of Engineering Science*, *92*, 47–62.

Montalvão, D. (2010). *A modal-based contribution to damage location in laminated composites*

plates. PhD thesis, Instituto Superior Técnico, Universidade de Lisboa, Portugal.
Montalvao, D., Maia, N. M. M., & Ribeiro, A. M. R. (2006). A Review of Vibration Based Structural Health Monitoring with Special Emphasis on Composite Materials. *The Shock and Vibration Digest*, *38*(4), 295–324.
Montalvão, D., Ribeiro, A. M. R., & Duarte-Silva, J. (2009). A method for the localization of damage in a CFRP plate using damping. *Mechanical Systems and Signal Processing*, *23*(6), 1846–1854.
Montalvão, D., Ribeiro, A. M. R., & Duarte-Silva, J. A. B. (2011). Experimental Assessment of a Modal-Based Multi-Parameter Method for Locating Damage in Composite Laminates. *Experimental Mechanics*, *51*(9), 1473–1488.
Montalvão, D., & Silva, J. M. M. (2015). An alternative method to the identification of the modal damping factor based on the dissipated energy. *Mechanical Systems and Signal Processing*, *54*(March 31), 108–123.
Montalvão Diogo, Dimitris Karanatsis, António MR Ribeiro, Joana Arina, R. B. (2014). An experimental study on the evolution of modal damping with damage in carbon fiber laminates. *Journal of Composite Materials*, *49*(19), 2403–2413.
Montanini, R., & Freni, F. (2012). Non-destructive evaluation of thick glass fiber-reinforced composites by means of optically excited lock-in thermography. *Composites Part A: Applied Science and Manufacturing*, *43*(11), 2075–2082.
Mustapha, S., Ye, L., Dong, X., & Alamdari, M. M. (2016). Evaluation of barely visible indentation damage (BVID) in CF/EP sandwich composites using guided wave signals. *Mechanical Systems and Signal Processing*, *76*, 497–517.
Mustapha, S., Ye, L., Wang, D., & Lu, Y. (2011). Assessment of debonding in sandwich CF/EP composite beams using A0 Lamb wave at low frequency. *Composite Structures*, *93*(2), 483–491.
Nairn, J. A. (1992). *NASA Contractor Report 4479*. *NASA Contractor Report 4472*. Salt Lake City, Utah.
Nairn, J. A. (2000). Matrix Microcracking in Composites. In *Polymer Matrix Composites* (Vol. 2, pp. 1–34). Elsevier Science.
Nairn, J. A., & Hu, S. (1994). Micromechanics of damage: a case study of matrix microcracking. *Damage Mechanics of Composite Materials*, 187–243.
Nauman, S., Cristian, I., & Koncar, V. (2011). Simultaneous Application of Fibrous Piezoresistive Sensors for Compression and Traction Detection in Glass Laminate Composites. *Sensors*, *11*(10), 9478–9498.
Neto, P., Alfaiate, J., & Vinagre, J. (2016). Assessment of the dependence of CFRP-concrete behaviour on the width of the bonded materials. *Composites Part B: Engineering*, *91*, 448–457.
Ng, C. T., & Veidt, M. (2009). A Lamb-wave-based technique for damage detection in composite laminates. *Smart Materials and Structures*, *18*(7), 74006.
Ng, S. C., Ismail, N., Ali, A., Sahari, B., Yusof, J. M., & Chu, B. W. (2011). Non-destructive Inspection of Multi-layered Composite Using Ultrasonic Signal Processing. In *IOP Conference Series: Materials Science and Engineering* (Vol. 17, p. 12045). IOP Publishing.
Ning Hu, Shimomukai, T., Fukunaga, H., & Zhongqing Su. (2008). Damage Identification of Metallic Structures Using A0 Mode of Lamb Waves. *Structural Health Monitoring*, *7*(3), 271–285.
Noorsuhada, M. N. (2016). An overview on fatigue damage assessment of reinforced concrete structures with the aid of acoustic emission technique. *Construction and Building Materials*, *112*, 424–439.
Notta-Cuvier, D., Lauro, F., Bennani, B., & Balieu, R. (2014). Damage of short-fibre reinforced materials with anisotropy induced by complex fibres orientations. *Mechanics of Materials*,

68, 193–206.
Novo, P. J., Silva, J. F., Nunes, J. P., & Marques, A. T. (2016). Pultrusion of fibre reinforced thermoplastic pre-impregnated materials. *Composites Part B: Engineering*, *89*(March 15), 328–339.
Okabe, Y., Fujibayashi, K., Shimazaki, M., Soejima, H., & Ogisu, T. (2010). Delamination detection in composite laminates using dispersion change based on mode conversion of Lamb waves. *Smart Materials and Structures*, *19*(11), 115013.
Ooijevaar, T. H., Loendersloot, R., Warnet, L. L., de Boer, A., & Akkerman, R. (2010). Vibration based structural health monitoring of a composite T-beam. *Composite Structures*, *92*(9), 2007–2015.
Ooijevaar, T. H., Rogge, M. D., Loendersloot, R., Warnet, L. L., Akkerman, R., & Tinga, T. (2015). Nonlinear dynamic behavior of an impact damaged composite skin-stiffener structure. *Journal of Sound and Vibration*, *353*, 243–258.
Othman, A., Abdullah, S., Ariffin, A. K., & Mohamed, N. A. N. (2014). Investigating the quasi-static axial crushing behavior of polymeric foam-filled composite pultrusion square tubes. *Materials and Design*, *63*, 446–459.
Park, C. ., & McManus, H. . (1996). Thermally induced damage in composite laminates: predictive methodology and experimental investigation. *Composites Science and Technology*, *56*(10), 1209–1219.
Peng, T., Liu, Y., Saxena, A., & Goebel, K. (2015). In-situ fatigue life prognosis for composite laminates based on stiffness degradation. *Composite Structures*, *132*, 155–165.
Pérez, M. A., Gil, L., & Oller, S. (2014). Impact damage identification in composite laminates using vibration testing. *Composite Structures*, *108*(February 28), 267–276.
Pieczonka, L., Ukowski, P., Klepka, A., Staszewski, W. J., Uhl, T., & Aymerich, F. (2014). Impact damage detection in light composite sandwich panels using piezo-based nonlinear vibro-acoustic modulations. *Smart Materials and Structures*, *23*(10), 105021.
Pimenta, S., Gutkin, R., Pinho, S. T., and Robinson, P. (2009a). A micromechanical model for kink-band formation: Part I — Experimental study and numerical modelling. *Composites Science and Technology*, *69*(7), 948–955.
Pimenta, S., Gutkin, R., Pinho, S. T., and Robinson, P. (2009b). A micromechanical model for kink-band formation: Part II—Analytical modelling. *Composites Science and Technology*, *69*(7), 956–964.
Pochiraju, K. V., Lau, A. C. W. and Wang, A. S. D. (1995). Analysis of fiber pull out or push-in with frictional sliding at the fiber-matrix interface. *Composites Engineering*, *5*(6), 611–631.
Potel, C., Chotard, T., de Belleval, J.-F., & Benzeggagh, M. (1998). Characterization of composite materials by ultrasonic methods: modelization and application to impact damage. *Composites Part B: Engineering*, *29*(2), 159–169.
Ramadas, C., Padiyar, J., Balasubramaniam, K., Joshi, M., & Krishnamurthy, C. V. (2011). Lamb wave based ultrasonic imaging of interface delamination in a composite T-joint. *NDT and E International*, *44*(6), 523–530.
Rathod, V. T., & Roy Mahapatra, D. (2011). Ultrasonic Lamb wave based monitoring of corrosion type of damage in plate using a circular array of piezoelectric transducers. *NDT and E International*, *44*(7), 628–636.
Ribeiro, A. M. R., Maia, N. M. M., & Silva, J. M. M. (2000). Response prediction from a reduced set of known responses using the transmissibility. *Proceedings of the International Modal Analysis Conference - IMAC*.
Ribeiro, A. M. R., Silva, J. M. M., & Maia, N. M. M. (2000). On the generalisation of the transmissibility concept. *Mechanical Systems and Signal Processing*, *14*(1), 29–35.
Ribeiro, A., Maia, N., & Silva, J. (1999). Experimental evaluation of the transmissibility matrix. *SPIE Proceedings Series*, 1126–1129.

Rilo, N.F., Ferreira, L.M.S. and Leal, R. A. C. P. (2006). Low-velocity impact analysis of glass/epoxy plates. In *In Proceedings of the 5th International Conference on Mechanics and Materials in Design (M2D'2006)* (Vol. 110, p. 92). Porto, Portugal.

Ryles, M., Ngau, F. H., Mcdonald, I., & Staszewski, W. J. (2008). Comparative study of nonlinear acoustic and Lamb wave techniques for fatigue crack detection in metallic structures. *Fatigue & Fracture of Engineering Materials & Structures*, *31*(8), 674–683.

Rytter, A. (1993). *Vibrational Based Inspection of Civil Engineering Structures*. *Fracture and Dynamics*. Aalborg University, Denmark.

Sahin, M. and Shenoi, R.A. (2003). Vibration-based damage identification in beam-like composite laminates by using artificial neural networks. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *217*(6), 661–676.

Salas, M., Focke, O., Herrmann, A. ., & Lang, W. (2014). Wireless Power Transmission for SHM of Fibre reinforced composite materials. *Sensors Journal, IEEE*, *14*(7), 2171–2176.

Sampaio, R.P.C., Maia, N., Ribeiro, A.M.R. and Silva, J. (2001). Transmissibility techniques for damage detection. *In Proceedings of the International Modal Analysis Conference*, *2*, 1524–1527.

Sarigül, A. S., & Karagözlü, E. (2014). Vibro-acoustic analysis of composite plates. *Journal of Physics: Conference Series*, *490*(1), 12212.

Sause, M. G. R., Müller, T., Horoschenkoff, A., & Horn, S. (2012). Quantification of failure mechanisms in mode-I loading of fiber reinforced plastics utilizing acoustic emission analysis. *Composites Science and Technology*, *72*(2), 167–174.

Schön, J. (2000). A model of fatigue delamination in composites. *Composites Science and Technology*, *60*(4), 553–558.

Schwab, M., Todt, M., Wolfahrt, M., & Pettermann, H. E. (2016). Failure mechanism based modelling of impact on fabric reinforced composite laminates based on shell elements. *Composites Science and Technology*, *128*, 131–137.

Selman, E., Ghiami, A., & Alver, N. (2015). Study of fracture evolution in FRP-strengthened reinforced concrete beam under cyclic load by acoustic emission technique: An integrated mechanical-acoustic energy approach. *Construction and Building Materials*, *95*, 832–841.

Shahdin, A., Mezeix, L., Bouvet, C., Morlier, J., & Gourinat, Y. (2009). Monitoring the effects of impact damages on modal parameters in carbon fiber entangled sandwich beams. *Engineering Structures*, *31*(12), 2833–2841.

Sharma, A., Sharma, S., Sharma, S., & Mukherjee, A. (2015). Ultrasonic guided waves for monitoring corrosion of FRP wrapped concrete structures. *Construction and Building Materials*, *96*, 690–702.

Sheela, K. G., & Deepa, S. N. (2013). Review on methods to fix number of hidden neurons in neural networks. *Mathematical Problems in Engineering*, *2013*.

Shilbayeh, N. and Iskandarani, M.Z. (2004). Application of new feature extraction technique to PVT images of composite structures. *Inform Technol J*, *3*(3), 332–336.

Shyr, T.-W., & Pan, Y.-H. (2003). Impact resistance and damage characteristics of composite laminates. *Composite Structures*, *62*(2), 193–203.

Steiner, K. V, Eduljee, R. F., Huang, X., & Gillespie Jr, J. W. (1995). Ultrasonic NDE techniques for the evaluation of matrix cracking in composite laminates. *Composites Science and Technology*, *53*(2), 193–198.

Su, Z., & Ye, L. (2009). *Identification of damage using Lamb waves: from fundamentals to applications* (Vol. 48). Springer Science & Business Media.

Su, Z., Ye, L., & Lu, Y. (2006). Guided Lamb waves for identification of damage in composite structures: A review. *Journal of Sound and Vibration*, *295*(3–5), 753–780.

Sung, D., Kim, C., & Hong, C. (2002). Monitoring of impact damages in composite laminates using wavelet transform. *Composites Part B: Engineering*, *33*(1), 35–43.

Surace, C., & Worden, K. (2011). Extended Analysis of a Damage Prognosis Approach Based on Interval Arithmetic. *Strain*, *47*(6), 544–554.
Sutherland, L. S., & Guedes Soares, C. (2012). The use of quasi-static testing to obtain the low-velocity impact damage resistance of marine GRP laminates. *Composites Part B: Engineering*, *43*(3), 1459–1467.
Suzuki, Y., Todoroki, A., Mizutani, Y., & Matsuzaki, R. (2011). Impact Damage Detection in CFRP Using Statistical Analysis of Resistance-Temperature Characteristics. *Journal of Solid Mechanics and Materials Engineering*, *5*(1), 33–43.
Svensson, D.,Alfredsson, K. S., Stigh, U., and Jansson, N. E. (2016). Measurement of cohesive law for kink-band formation in unidirectional composite. *Engineering Fracture Mechanics*, *151*, 1–10.
Swamy, R. ., & Mukhopadhyaya, P. (1999). Debonding of carbon-fibre-reinforced polymer plate from concrete beams. *Proceedings of the Institution of Civil Engineers. Structures and Buildings*, *134*(4), 301–317.
Tashan, J., & Al-mahaidi, R. (2012). Investigation of the parameters that influence the accuracy of bond defect detection in CFRP bonded specimens using IR thermography. *Composite Structures*, *94*(2), 519–531.
Tjirkallis, A., & Kyprianou, A. (2016). Damage detection under varying environmental and operational conditions using Wavelet Transform Modulus Maxima decay lines similarity. *Mechanical Systems and Signal Processing*, *66–67*(January 31), 282–297.
Tong, J., Guild, F. J., Ogin, S. L., & Smith, P. A. (1997). On matrix crack growth in quasi-isotropic laminates-I. Experimental investigation. *Composites Science and Technology*, *57*(11), 1527–1535.
Torres-Arredondo, M. A., Tibaduiza, D. A., McGugan, M., Toftegaard, H., Borum, K. K., Mujica, L. E., … Fritzen, C. P. (2013). Multivariate data-driven modelling and pattern recognition for damage detection and identification for acoustic emission and acousto-ultrasonics. *Smart Materials and Structures*, *22*(10), 105023.
Van Den Abeele, K.A. Johnson, P. A., & Sutin, A. (2000). Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, part I: nonlinear wave modulation spectroscopy (NWMS). *Research in Nondestructive Evaluation*, *12*(1), 17–30.
Varga, M., Vretenar, V., Kotlar, M., Skakalova, V., & Kromka, A. (2014). Fabrication of free-standing pure carbon-based composite material with the combination of sp2-sp3 hybridizations. *Applied Surface Science*, *308*, 211–215.
Vary, A. (1981). Acousto-ultrasonic characterization of fiber reinforced composites.
Vary, A., & Bowles, K. . (1978). Use of an ultrasonic-acoustic technique for nondestructive evaluation of fiber composite strength. *Nasa Technical Memorandum*.
Vaughan, T. ., & McCarthy, C. . (2011). A micromechanical study on the effect of intra-ply properties on transverse shear fracture in fibre reinforced composites. Part A. *Applied Science and Manufacturing*, *42*(9), 1217–1228.
Viets, C., Kaysser, S., & Schulte, K. (2014). Damage mapping of GFRP via electrical resistance measurements using nanocomposite epoxy matrix systems. *Composites Part B: Engineering*, *65*, 80–88.
Vinet, A., and Gamby, D. (2008). Prediction of long-term mechanical behaviour of fibre composites from the observation of micro-buckling appearing during creep compression tests. *Composites Science and Technology*, *68*(2), 526–536.
Vogler, T. J., and Kyriakides, S. (1997). Initiation and axial propagation of kink bands in fiber composites. *Acta Materialia*, *45*(6), 2443–2454.
Vogler, T. J., & Kyriakides, S. (1999). On the axial propagation of kink bands in fiber composites : Part i experiments. *International Journal of Solids and Structures*, *36*(4), 557–574.
Wang, S., Chung, D. D. L., & Chung, J. H. (2005). Impact damage of carbon fiber polymer-matrix

composites, studied by electrical resistance measurement. *Composites Part A: Applied Science and Manufacturing*, *36*(12), 1707–1715.

Wang, Z.-X., Qiao, P., & Xu, J. (2015). Vibration analysis of laminated composite plates with damage using the perturbation method. *Composites Part B: Engineering*, *72*(April 30), 160–174.

Watkins, S. ., Akhavan, F., Dua, R., Chandrashekhara, K., & Wunsch, D. C. (2007). Impact-induced damage characterization of composite plates using neural networks. *Smart Materials and Structures*, *16*(2), 515–524.

Wen, J., Xia, Z., & Choy, F. (2011). Damage detection of carbon fiber reinforced polymer composites via electrical resistance measurement. *Composites Part B: Engineering*, *42*(1), 77–86.

Wind, J. L., Steffensen, S., and Jensen, H. M. (2014). Comparison of a composite model and an individually fiber and matrix discretized model for kink band formation. *International Journal of Non-Linear Mechanics*, *67*, 319–325.

Yam, L. H., Yan, Y. J., & Jiang, J. S. (2003). Vibration-based damage detection for composite structures using wavelet transform and neural network identification. *Composite Structures*, *60*(4), 403–412.

Yang, C., Ye, L., Su, Z., & Bannister, M. (2006). Some aspects of numerical simulation for Lamb wave propagation in composite laminates. *Composite Structures*, *75*(1–4), 267–275.

Ye Lin, Ye Lu, Zhongqing Su, G. M. (2005). Functionalized composite structures for new generation airframes: a review. *Composites Science and Technology*, *65*(9), 1436–1446.

Yi, X., Zhu, D., Wang, Y., Guo, J., & Lee, K.-M. (2010). Transmissibility-function-based structural damage detection with tetherless mobile sensors. *Proceedings of the 5th International Conference on Bridge Maintenance, Safety and Management (IABMAS)*, 328–335.

Yin, W., Withers, P. J., Sharma, U., & Peyton, A. J. (2009). Noncontact Characterization of Carbon-Fibre-Reinforced Plastics Using Multifrequency Eddy Current Sensors. *Instrumentation and Measurement Technology Conference Proceedings, 2007. IMTC 2007. IEEE*, *58*(3), 738–743.

Yoder, N. C., & Adams, D. E. (2010). Vibro-Acoustic Modulation Utilizing a Swept Probing Signal for Robust Crack Detection. *Structural Health Monitoring*, *9*(3), 257–267.

Yue, C. Y., and Padmanabhan, K. (1999). Interfacial studies on surface modified Kevlar fibre/epoxy matrix composites. *Composites Part B: Engineering*, *30*(2), 205–217.

Yun, H. Do, Choi, W. C., & Seo, S. Y. (2010). Acoustic emission activities and damage evaluation of reinforced concrete beams strengthened with CFRP sheets. *NDT and E International*, *43*(7), 615–628.

Zhang, J., & Zhang, X. (2015). Simulating low-velocity impact induced delamination in composites by a quasi-static load model with surface-based cohesive contact. *Composite Structures*, *125*, 51–57.

Zhang, J., Zhao, L., Li, M., & Chen, Y. (2015). Compressive fatigue behavior of low velocity impacted and quasi-static indented CFRP laminates. *Composite Structures*, *133*, 1009–1015.

Zhao, X., Royer, R. L., Owens, S. E., & Rose, J. L. (2011). Ultrasonic Lamb wave tomography in structural health monitoring. *Smart Materials and Structures*, *20*(10), 105002.

Zheng, Z., and Engblom, J. J. (2002). Fiber micro-buckling of continuous glass-fiber reinforced hollow-cored recycled plastic extrusions under long-term flexural loads. *Composite Structures*, *56*(2), 157–164.

Zhou, C., Hong, M., Su, Z., Wang, Q., & Cheng, L. (2013). Evaluation of fatigue cracks using nonlinearities of acousto-ultrasonic waves acquired by an active sensor network. *Smart Materials and Structures*, *22*(1), 15018.

Zhou, Y. L., Perera, R., & Sevillano, E. (2012). Damage Identification from Power Spectrum Density Transmissibility. *Proceedings of the 6th European Workshop on Structural Health Monitoring*, 1–7.

Zi, G., and Bažant, Z. P. (2003). Eigenvalue method for computing size effect of cohesive cracks with residual stress, with application to kink-bands in composites. *International Journal of Engineering Science*, *41*(13), 1519–1534.

Zuluaga-Ramírez, P., Arconada, Á., Frövel, M., Belenguer, T., & Salazar, F. (2015). Optical sensing of the fatigue damage state of CFRP under realistic aeronautical load sequences. *Sensors*, *15*(3), 5710–5721.

Zuluaga-Ramírez, P., Frövel, M., Belenguer, T., & Salazar, F. (2015). Non contact inspection of the fatigue damage state of carbon fiber reinforced polymer by optical surface roughness measurements. *NDT and E International*, *70*(March 31), 22–28.

Zumpano, G., & Meo, M. (2008a). Damage detection in an aircraft foam sandwich panel using nonlinear elastic wave spectroscopy. *Computers and Structures*, *86*(3–5), 483–490.

Zumpano, G., & Meo, M. (2008b). Damage localization using transient non-linear elasticwave spectroscopy on composite structures. *International Journal of Non-Linear Mechanics*, *43*(3), 217–230.