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An Extensive Overview of Lamb Wave Technique for Detecting Fatigue Damage in Composite Structures

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Abstract

Lamb waves are guided waves and have many useful properties that can be exploited for non-destructive testing (NDT) and structural health monitoring (SHM) applications. Utilization of Lamb waves for these purposes have led to the development of some of the most promising methods and have resulted in numerous useful and practical applications over the past two decades. The major advantage of using Lamb waves has been their capability of propagating a relatively long distance in plate or shell structures, the ability to follow curvature and penetrate into hidden and buried parts, allowing the detection of faults between the layers of composite laminate structures. The wave structure depends on the frequency and phase velocity. Lamb waves are on the verge of maturity for diverse engineering applications. This emerging technique serves as an encouraging candidate for facilitating continuous and automated surveillance of the integrity of engineering structures in a cost-effective manner. Numerous studies of lamb wave based methodologies have been developed for damage detection in composite structures. In this paper we present an overview of lamb waves behavior, modeling and applications as well as their limitations for fatigue damage detection of composite structures. The focus of this study is on the application of Lamb waves combined with Artificial Neural Networks. Over the last decade, ANNs have been used as one of the most desirable methods for fatigue damage prediction of composite structures. A well-trained ANN can predict outcomes under an unknown stimulus based on pre-accumulated knowledge from a lamb waves sensing system, while avoiding interrogating intricate constitutive relations and save the time needed for this interrogation. An overview of some new developments in this regard is presented.

Keywords

Lamb Wave Technique, Piezoelectric Transducers (PZTs), Fatigue Damage Detection, Composite Structures, Artificial Neural Networks (ANNs)

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1. Introduction

Composite materials are now commonly used in a wide range of engineering applications. They now play an important role in aerospace, mechanical, and structural engineering as well as in automotive, construction, ship building, submarines, nuclear and chemical industries and facilities. In all these applications, they offer a viable alternative to metallic materials by providing high stiffness and strength to weight ratios and improving fatigue resistance and damage tolerance capability.

The ever increasing application of composite materials in various engineering applications, in particular in structural, aerospace and mechanical systems has posed new challenges.

Stricter requirements for the safety, longevity, reliability and safety of new composite structures, and application of

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composite materials in existing structures, on one hand, and the development of advanced sensing technologies for monitoring the state of the integrity of these structures on the other hand, have resulted in, and mandated, the development of monitoring and assessment methodologies for real-time, and online detection and the identification of damage in composite structures.

Damages like fiber breakage, matrix cracking, debonding between the fibers and the matrix, and delaminations or interlayer cracks are typical damages in composite laminate structures. These damages can significantly reduce the strength and structural integrity. Early detection or monitoring is the key to prevent a catastrophic failure of these structures, which in most cases are expected to perform well near their limit conditions. Such a monitoring system will provide information concerning the development of structural damages, which can be used to implement schedule for maintenance or repair to assure the safety and integrity of structures. One of the possible means to achieve this goal is the development and utilization of a reliable and efficient Structural Health Monitoring (SHM) system. By providing additional safety measures, the SHM systems enable the life of the structures to be maximized and reduce the structural life costs.

Over the last two decades SHM has emerged as a research area with different applications ranging from rotating machineries, offshore platforms, space vehicles and aircrafts to bridges [1, 2]. It is highly desirable to have SHM systems in structures for which failures would result in a catastrophic loss of life, i.e. in composite structures. If the onset of the failures can be detected, actions can be taken to limit or prevent the use of these structures, while repairs can be carried out.

SHM sets out to determine the health of a structure by collected data from a network of sensors that are permanently installed onto the structure and monitored over time. The objective of an SHM system if to first perform a diagnosis of the structural safety and health, followed by prognosis of the remaining life. SHM can be performed in a passive or active way. Passive SHMs are a network of sensors that “listen” to the structure to monitor whether the component is signaling any changes. Active SHM uses a network of active sensors that interrogate the structural health through active sensors and thus, determine the presence or absence of damage. Over the past few years, a wide range of quantitative data analysis techniques have been reported in the literature that have been successfully developed and implemented, as part of an SHM system, for damage detection in metallic and composite structures. Most of these techniques are based on non-destructive (ND) methods.

Lamb waves have great potential for damage detection in composite structures. In comparison with other NDE approaches, Lamb waves can offer faster and more cost-effective evaluation of various types of damage. However, the method requires extensive experience for application in monitoring complex structures. Lamb waves are particularly attractive due to their ability of inspecting large structures with a small number of transducers. However, deciding the positions of the transducers is one of the most important problems associated with the method. The use of piezoelectric transducers (PZTs) along with guided Lamb waves is a method that has received considerable attention due to the advantages in weight, cost, and function of the systems based on these elements [3, 4]. Lamb wave inspection is based on waves propagating in plate-like structures. These waves interact with the damage. Baseline signals, representing ‘no damage’ condition, need to be obtained in order to see the changes in Lamb wave responses.

Lamb waves are useful for NDE for several reasons. They can travel long distances, even in high attenuation materials such as composites. They have a high susceptibility to interference along and around the propagation path [5], as a result of which large areas, such as a composite wing skin of an aircraft can be interrogated with ease. Lamb waves are also able to detect not only surface damage, but internal damage as well, since the entire thickness of the material can be interrogated using a variety of Lamb wave modes. Overall, Lamb wave based damage detection methods can be used to (1) inspect large structures without disturbing coating or insulation on the inspected structure; (2) inspect 100% of the cross-sectional area of a structure over a reasonably long length; (3) remove the need for expensive structural probing; (4) detect multiple defects; and (5) perform with very low energy and cost [5].

In this study, by utilizing the data collected from the literature on Lamb wave, we demonstrate how Lamb Wave method can be used to the diagnose the location, type and the severity of the fatigue damage in FRP composite structures. Furthermore, we will also present how, based on the information obtained regarding the damage, we can accurately estimate the fatigue life of FRP composite structures.

Over the past few years, a wide range of lamb wave based methodologies have been developed for damage detection in composite structures. Optimal location of sensors, system identification methods, and finite element analysis pertaining to fatigue life estimation and damage detection in composite structures have also been extensively studied. It is worth noting that Artificial Neural Networks has been one of the most promising techniques that has been used in recent years for fatigue damage prediction of composite structures. In the research study presented herein, we will utilize an ANN based algorithm for the aforementioned damage detection and fatigue life estimation.

It is important to point out that in studying the fatigue damage detection in composite structures, using the Lamb waves technique, there are a few important issues that must be examined before the fatigue detection analysis is carried out. These issues have been thoroughly studied in this paper. First, the mechanical properties and attributes of the composite material must be understood. This includes the failure mechanisms and fatigue behavior of the composite material under investigation and the effect of fatigue loading. Subsequently, an examination of the most widely used NDE methods for detecting the fatigue damage of composite structures needs to be conducted. Finally, a comparison needs to be made between the results presented in the literature and those obtained in the current study in order to show the advantages of the methodology developed and implemented in this research.

1.1. Composite Materials

The use of composite materials in structural applications has drastically increased in recent years. The major advantages of composite materials are their unique mechanical properties, in particular the specific strength and specific stiffness, also improved fatigue resistance and damage tolerance capability. It has been due to these properties that composite materials are now extensively used and are becoming the dominant type of material in structural applications, automotive, aerospace, marine and by sports equipment industries. For example in aircraft structures composites are now widely used in, wings, trailing-edge panels and stabilizers. The new Boeing B787 has extensively incorporated composite materials in the structure of the aircraft, including the fuselage, which is entirely made of composite materials [6]. Figure 1 shows the extent of composite materials used in various parts of Boeing 787 [7].

The important mechanical properties of composite materials are strength, stiffness and fatigue life, which make them imperative to determine structures integrity and reliability. During last decades, composite structures have become as one of the most challenging areas of research due to their increasing use in a wide range of applications ranging from mechanical to structural systems. These challenges re mainly associated with the fact that composite structures are subjected to a combination of static and dynamic loading, such as fatigue. It is widely recognized that about 80% of the failures of mechanical/structural components and systems are related to fatigue [8].

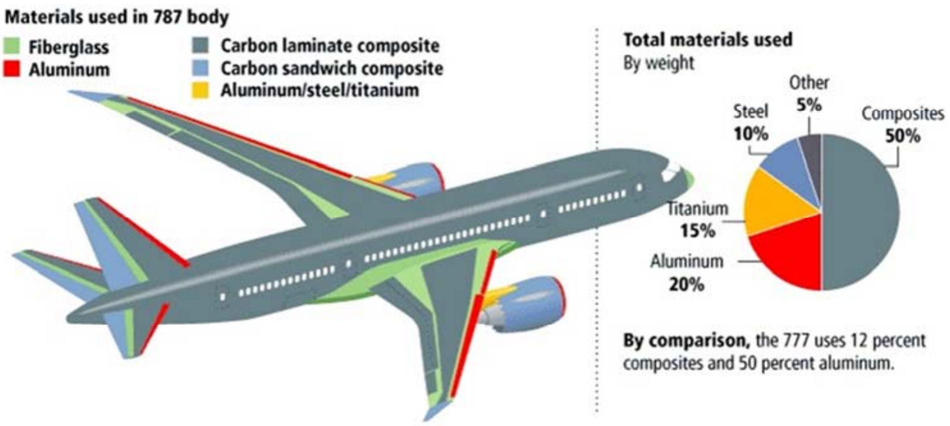


Figure 1. Extent of the usage of composite materials in Boeing 787 [7].

1.2. Failure Mechanisms in Composite Materials

Due to anisotropic characteristics of composite materials different failure modes can occur simultaneously or successively before the entire structure fails.

Generally, failure of composites under static loading occurs by a combination of various interacting mechanisms leading to the final rupture. In the case of laminates, as well as in a single lamina, different kinds of damage mechanisms can be found. Failure usually occurs at the interface between the matrix and reinforcement (i.e., debonding), especially on defects, which are always present in composites, mainly due to the manufacturing process. Other common types of failure modes are: matrix cracking, fiber rupture, delamination (in laminates) and buckling (in compression) [9].

During fatigue, damage starts very early, the basic influences of fatigue behavior and damage mechanisms of composites under uniaxial [10-13] and Multi-axially [14-16] fatigue loaded composites are the same and well understood. Fatigue damage can be divided into three successive stages: matrix cracking (phase I), development of local delamination caused by matrix cracks (phase II), and consolidation of local delamination leading to final failure (phase III). The stiffness behavior is also divided into three stages: rapid decrease triggered by matrix cracking within the first 10–20% of fatigue life (phase I), followed by a weak quasi-linear decrease (phase II). Subsequently, the damage rapidly develops and the material expereicnes ‘‘sudden death” in the end period of fatigue life (phase III) [17], as shown in Figure 2 [18].

Schulte et al. [19, 20] first reported these three phases in stiffness reduction and it has, since then, been observed in many different types of composite materials, and also in woven composites [21, 22].

Since the failure damage of fiber reinforced composites consists of three different phases, failure can occur in any of the phases or at their interface. Thus, the failures which could develop in reinforced composites are fiber breakage, matrix cracks, de-bonding and delamination (Figure 3).

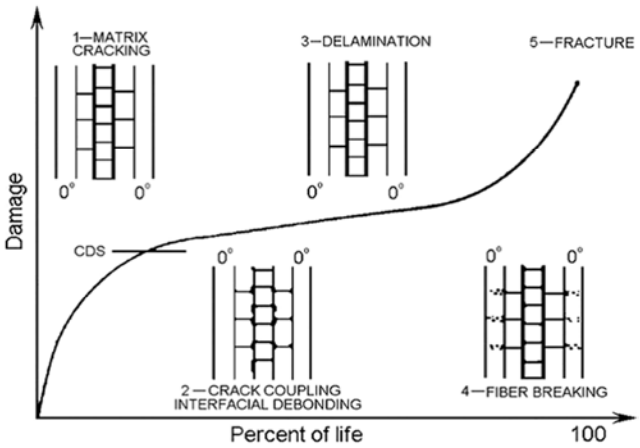


Figure 2. Fatigue damage evolution in composite laminates [18].

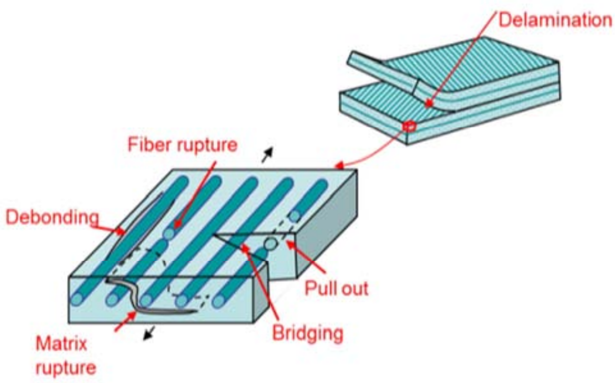


Figure 3. Failure modes in fiber reinforced composites.

1.3. Fatigue Behavior of Composite Materials

The behavior of composite materials subjected to fatigue loading is very complex due to nonhomogeneous and anisotropic properties, and it has been studied for a long time; however, the design of composite materials is still based on very long fatigue tests and high safety factors are used [23]. One of the earliest work on the fatigue mechanism of unidirectional (UD) composites under axial tension–tension loading was done by Dharan [24, 25], who elucidated the roles of the fibers, the matrix and their interface in causing fatigue failure of composites. He succeeded in developing a conceptual framework for explaining fatigue damage, known as the fatigue life diagram, as shown in Figure 4. The three regions of fatigue have been defined individually based on the dominant mechanisms operating in those regimes. Depending on the fiber, matrix, and interface properties, the regions will place themselves differently on the fatigue life diagram (FLD). As a baseline construction, the three regions are placed as depicted in Figure 4. It should be noted that Region I in the FLD is the quasi-static failure scatter band, independent of load cycling, and therefore, it does not depend only upon the matrix. The other two regions, Regions II and III, are primarily dependent upon the matrix fatigue properties, but are affected by fiber properties such as the fiber stiffness, fiber-matrix interface, matrix inelasticity, and fatigue load mode [26].

For example, considering the mechanisms operating in Region II of the FLD, it can be surmised that with stiffer fibers the cyclic growth of a fiber-bridged crack will be retarded, leading to longer fatigue life. Furthermore, the arresting of matrix fatigue cracks by stiffer fibers is expected to be more effective, resulting in enhancement of the fatigue limit. The arrows in Figure 4 mark these trends [26]. The fiber stiffness effect on fatigue limit of the epoxy matrix is reported by Dharan [24]. He conducted the test data for a carbon-epoxy composite and its FLD are also shown in Figure 5. By comparison of the FLDs of glass-epoxy and carbon-epoxy, the shift of Region II to higher fatigue life from glass fibers to carbon fibers is evident.

Also the two regions, Regions II and III, in FLD depend on other very important factors, with high degree, these factors must be taken into consideration and can be arranged according to their influence on FLD: (1) Loading types [27, 28]; (2) Loading frequency [29-31]; (3) Volume fraction (V_f) [32-34]; (4) Fiber orientation [35, 36] ; (5) Mean stress and stress ratio [37, 38]; (6) Environmental factors [39, 40]; (7) Sizing and stress gradient [41, 42]; (8) Surface finish [43, 44], and (9) Stress concentration [41, 45].

1.4. Fatigue Failure Criteria

Under fatigue loading conditions, the material is loaded by a stress state which is less than the maximum strength of the material, therefore there is no static mode of failure. However, by increasing the number of cycles, the material properties degrade and eventually lower to the level of the stress state and, at this point, catastrophic failure occurs. The idea of using polynomial failure criteria to predict the life of a composite material under fatigue loading has been utilized by many investigators [46–51]. They used the fatigue strength, as a function of number of cycles, in the denominators of failure criteria instead of the static strength of the material. This strategy is potentially beneficial in fatigue damage detection and prediction, so this development of failure models to characterize the mechanisms that lead to failure has been the matter of rigorous studies for over 30 years by researchers around the world. At present, countless theories are available in the literature that describe failure in various ways.

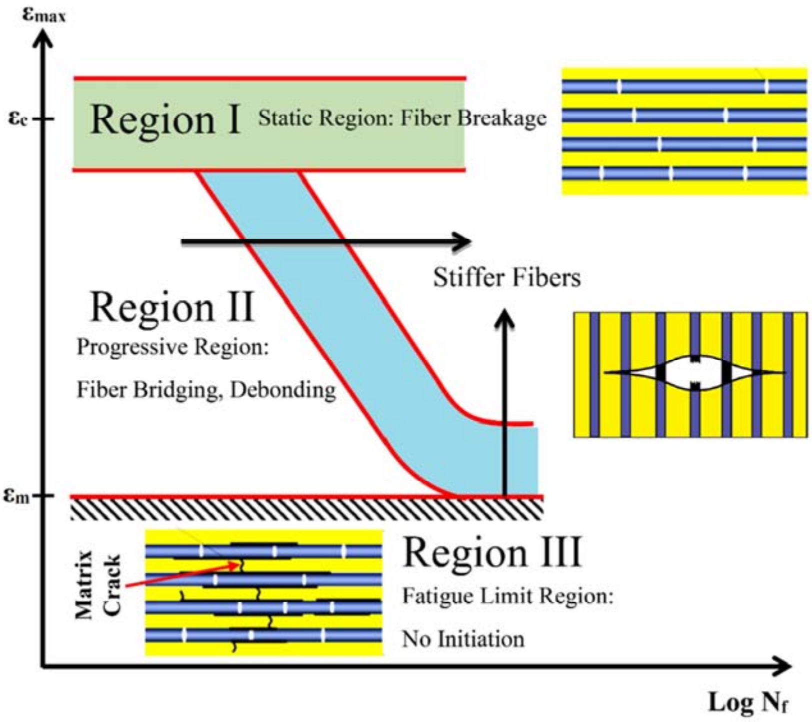


Figure 4. Fatigue life diagram (FLD) for UD composites for axial tension–tension loading.

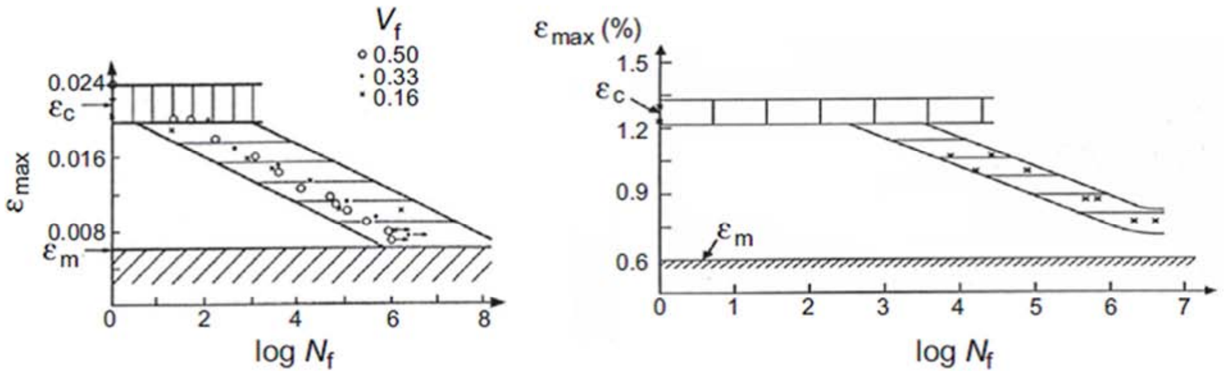


Figure 5. Fatigue life data and superimposed FLD for a glass-epoxy composite (left) at three fiber volume fractions and for a carbon-epoxy composite (right) [24].

In all criteria, all stress components interact and contribute simultaneously toward the failure of the composite systems. Therefore, the suitability of a certain criterion differs greatly according to the tested material, and its stress state. In the governing equations for all failure criteria, the right hand side is the unity, and the left hand side is comprised of the local stress components divided by their corresponding strengths. Therefore, the left hand side of any criterion is named the Relative Damage (R.D.).

2. Fatigue Damage Detection of Composite Structures

Rytter [52] introduced a damage state classification system which has been widely accepted by the community dealing with damage detection and by the structural health monitoring community. Following these lines, the damage state is described by answering the following questions: Is there damage in the system? (existence); Where is the damage in the structure? (location); What kind of damage is present? (type); How severe is the damage? (extension); and How much useful life remains? (prognosis).

Generally, identification of the damage type and its extent require prior knowledge of the structural behavior in the presence of each of the possible expected failure modes and their correlation with experimental data to be collected. This is normally achieved by resorting to analytical models. For example, in online monitoring, the modal parameters of the damaged structure must be compared with the parameters of the structure in its undamaged state, namely referred to as global diagnosis. Once the existence of damage existence is verified, the model of the structure in a damaged state may be used to determine the damage location, in what is called local diagnosis [53].

Fatigue damage detection in composite structures can be divided into two methods: destructive testing and non-destructive testing. Destructive testing may include using a variety of experimental methods and on-site visual inspections to test samples and to assess the possibility of failure e.g. tensile, compression, inter-laminar shear, shear and fracture toughness tests. Sectioning, de-plying and fractography are common methods of destructive testing for analyzing damaged composites structures.

Non-destructive testing (NDT) methods have been found to be useful for in-situ evaluation of composites structures, where the structural integrity of laminate composite structures can be assessed effectively. Over the past several years a wide range of methods have been implemented for the monitoring of laminate composite structures, including: (1) Ultrasonic [54-60]; (2) X-Ray Radiography [61-64]; (3) Thermography [65-69]; (4) Acoustic Emission [70-74]; (5) Vibrography [75-78]; (6) Eddy Currents [79]; (7) Optical-based nondestructive techniques, including embedded Optical Fiber Sensors [80-83], and (8) Lamb Wave [84-94].

Thus, there is a diverse range of NDE techniques for detecting fatigue damage in composite structures, and the capabilities and limitations of each method are different. Each technique has its specific field of applicability although there is a level of overlap according to the defect size and the accuracy of detection and the ability to detect certain types of damage. For example ultrasonics can detect delaminations whereas acoustic emission can identify delaminations and fiber failures, but no single method is capable of simultaneously detect all different fatigue damage modes [95]. Table 1 lists the types of fatigue damage that can be detected in laminate composite structures using NDE techniques.

As shown in Table 1, no single NDE technique has the capability to quantitatively relate the fatigue damage states in laminate composite structures to all different modes of fatigue damage. It is essential that more than one NDE method be used to gain as much information as possible about the different fatigue damage states and the residual mechanical properties of a composite. For example, it may be necessary to combine information gained from ultrasonics and X-ray radiography to achieve a three-dimensional map of the complex array of fatigue damage in a composite.

Table 1. Summary of capabilities of NDE techniques for detecting fatigue damage in laminates composite structures [95].

NDE technique	Damage to laminates		
	Transverse matrix cracks	**Delamination**	**Fiber fracture**
Ultrasonics	Yes	Yes	No
Lamb waves	Yes	Yes	No
Acoustic emission	Difficult	Yes	Yes
X-ray radiography	Yes	Yes	Boron fibers only
Thermography	Difficult	Yes	No
Vibrography	Yes	Yes	No
Eddy currents	No	No	Boron/carbon fibers only

3. Lamb Wave Method Based Damage Detection

Lamb waves are guided waves that propagate in plate or shell structures. There has been an increasing level of interest in using Lamb waves for identifying structural damage, entailing intensive research and development in this field over the past two decades. Now on the verge of maturity for diverse engineering applications, this emerging technique serves as an encouraging candidate for facilitating continuous and automated monitoring of the integrity of engineering structures in a cost-effective manner. In comparison with conventional nondestructive evaluation (NDE) techniques, such as ultrasonic scanning and radiography, which have been well developed over half a century, damage identification using Lamb waves is in a stage of burgeoning development, presenting a number of technical challenges in application that need to be addressed and circumvented.

Lamb waves are useful for NDE functions for several reasons: They can travel long distances, even in high attenuation materials such as composites. They have a high susceptibility to interference along and around the propagation path, as a result of which large areas, such as a composite wing skin of an aircraft, can be interrogated with ease. Lamb waves are also able to detect not just surface damage, but also internal damage because the entire thickness of the material can be interrogated using a variety of Lamb wave modes. Overall, Lamb wave based damage detection methods can be used to (1) inspect large structures without disturbing coating or insulation on the inspected structure; (2) inspect 100% of the cross-sectional area of a structure over a reasonably long length; (3) eliminate the need for expensive structural probing; (4) detect multiple defects; and (5) perform with very low energy and cost [96]. As stated earlier, by using data collected from the Lamb wave literature, and following the suggestions in the relevant literature, in this study Lamb Wave method in conjunction with an artificial neural network technique will be used to diagnose the location, types and severity of the fatigue damage in a composite structure. From this information, an accurate and useful life estimation of composite structures can also be determined.

3.1. History and Research

Lamb waves are elastic waves whose particle motion lies in the plane that contains the direction of wave propagation and the plate normal (the direction perpendicular to the plate). Lamb waves propagate in solid plates. Lamb waves, discovered in 1917 by Horace Lamb. He published his classic analysis and description of acoustic waves of this type. The properties of Lamb waves are quite complex. An infinite medium supports just two wave modes traveling at unique velocities; but it has been demonstrated that thin plate-like structures such as panels, plates, and small beams with parallel free boundaries support two infinite sets of Lamb wave modes, whose velocities depend on the relationship between wavelength and plate thickness [96]. Mindlin was the first to develop a comprehensive plate theory in parallel with work conducted by Schoch and Frederick between the mid-1950s and 1960s [97]. In 1961, Worlton [97] introduced Lamb waves as a means of damage detection. These work, together, established the utilization of Lamb waves today for non-destructive evaluation (NDE).

The first application of Lamb waves in composite materials was conducted by Saravanos and Birman [99]. They demonstrated both analytically and experimentally the possibility of detecting delamination in composite beams using Lamb waves. Similar conclusions were drawn by Percival and Birt [100], who began focusing their work on the two fundamental Lamb wave modes. Detection of other forms of damage in composite materials was also investigated by Seale and Smith [101], who examined fatigue and thermal damage, and Tang and Henneke [102], who observed the sensitivity of Lamb wave propagation to fiber fracture.

The first scholars to discuss interaction of Lamb waves with defects for non-destructive testing were Alleyne and Cawley [103]. Accordingly, Saravanos et al. [104] presented a procedure for delamination detection in composite materials using Lamb Waves and embedded piezoelectric (PZT) sensors. Piezoelectric patches were used to excite the first anti-symmetric Lamb wave (mode).

Since that time, significant research has been carried out on the effectiveness and feasibility of Lamb wave for damage evaluation in composites. Kessler et al. [105], carried out an extensive research to compare the utilization of Lamb waves for in composites with other techniques for damage detection, testing the durability and performance of Lamb waves and the effect of various parameters in order to assess Lamb waves' sensitivity as well as its capabilities and limitations in composite damage detection, including in finding damage location. Similar studies were also carried out by investigated by other investigators [106-112]. These studies concluded that the Lamb waves are more sensitive to local structural defects. However, despite the fact that Lamb waves display great capabilities in composite damage detection and location, a major disadvantage of this method is that its application requires a continuity is the propagation of the waves and as such, it requires a constant voltage supply and function generating signal. Another drawback is the high data acquisition rate needed to gain useful signal resolution. Finally, and nevertheless, the aforementioned studies found that the Lamb wave method is noticeably a more sensitive and a more accurate means for damage detection and location than other methods. However, to benefit from its capabilities and effectiveness, it should be placed utilized in a SHM system in conjunction with another passive detection method, such as frequency response functions (FRF) method or spectral analysis technique in order to conserve power and data storage space, since the Lamb wave data can be more difficult to interpret. It has also been demonstrated that Lamb wave data can be processed by using wavelet transform-based analysis in the time-frequency domain for the purpose of damage evaluation.

Over the last decade, new research endeavors were undertaken to develop Lamb wave based methods that could the aforementioned shortcomings and the challenges associated with the utilization of Lamb waves for detection of fatigue damages in composite structures. In order to develop more practical and more sensitive methods for the detection of damage detection and its location Yeum et al. [90] presented a new Lamb wave-based delamination detection methodology that allows detection of delamination in a single wave propagation path without using prior baseline data or a predetermined decision boundary. They extracted damage information from circular PZT signals used for Lamb wave excitation. These researchers conducted numerical simulation and experimental testing, to investigate the interaction between the single wave mode and delamination. Finally, they proposed a new reference-free delamination detection technique so that the delamination in a single wave path can be detected without being compared with prior baseline data or signals, or in other words it can be instantaneously obtained from multiple paths.

Lamb wave simulation was also undertaken in finite element analysis (FEA) using FE programs like ANSYS and ABAQUS using 2-D cross sectional plate model of the specimen to understand Lamb wave response and damage assessment performance for various degrees of fatigue damages such as debonding and delamination. Several approaches of finite element methods (FEM) were used for modelling the Lamb wave propagation in form of time domain modelling, using the two dimensional Fast Fourier Transform (2D FFT) [113] or Wavelet transform [114], Mode shape of short waveguides [115], Semi-Analytical Finite Element (SAFE) method, and Wave Finite Element (WFE) method [116]. Many researchers have used FEA for the verification of the experimental work results. Baid [117] has reported one of most comprehensive work in using FEA to verify the results of experimental work on a specimen containing damage on the skin or a localized de-bonding at the skin-core interfaces. He used a comprehensive approach including numerical (finite element method) and analytical methods for calculating the ultrasonic wave field in a woven composite panel and a sandwich plate consisting of an aluminum honeycomb core and woven composite face-sheets with and without defects. He detected by a distributed array of identical PZTs located on the surface of the specimen. Also Shen and Giurgiutiu [94] presented a combined analytical and finite element model approach (CAFA) for the accurate, efficient, and versatile simulation of 2-D Lamb wave propagation and interaction with damage. In the experimental work for Lamb wave propagation in specimen, by scanning laser Doppler vibrometry (SLDV) technique, conducted by Shen and Giurgiutiu, they compared the full-scale multiphysics FEM simulations and SLDV experiments. They found that the CAFA achieved remarkable performance in terms of computational accuracy, efficiency, and versatility.

3.2. Lamb Wave Modelling and Simulation

Lamb waves are ultrasonic guided waves that propagate between two parallel free surfaces and, as discussed, their use for damage detection has been widely explored and demonstrated. Damage in materials/structures can be detected by analyzing the difference between the phase/group velocity and the loss of amplitude of Lamb waves on damaged and un-damaged specimens. Lamb waves propagate in two types of modes; symmetrical (S) and anti-symmetry (A) modes (see Figure 6). In the S modes, the plate displacements are symmetrical with respect to its center plane, while in the A modes, they are anti-symmetrical. There are infinite number of modes (S and A) existing in a plate [118].

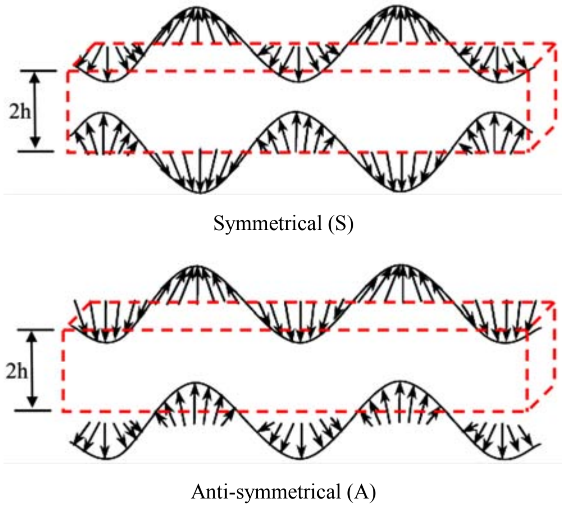


Figure 6. Symmetric and anti-symmetric Lamb wave modes.

The propagation characteristics of Lamb waves are described in the form of dispersion curves as shown in Figure 7, which are the plots of phase/group velocities versus the product of frequency-thickness generated by solving the Lamb wave equations.

The Lamb wave dispersion curves show the relationships between wavenumber k and circular frequency (or linear frequency f from equation). Phase velocity is obtained from the wavenumber by applying the relationship. For isotropic plates, an analytical expression for calculating the Lamb wave dispersion curves is available.

These dispersion curves are obtained from the solution of the Rayleigh- Lamb equation [119] given by:

$$\frac{tanh(\beta h)}{tanh(\alpha h)} = \left(-\left[\frac{4k^2 \alpha\beta}{\left(k^2 - \beta^2\right)^2} \right] \right)^{\pm 1} \tag{1}$$

Where: h is the half thickness of the plate. $\alpha^2 = \left(\omega^2 / c_p{}^2\right) - k^2$ and $\beta^2 = \left(\omega^2 / c_s{}^2\right) - k^2$, and c_s is the shear wave velocity. The plus sign in equation (1) is for the symmetric mode and the minus sign is for the anti-symmetric mode [120]. The Rayleigh–Lamb waves is a type of wave that propagates along a single surface. Both Rayleigh and Lamb waves are constrained by the elastic properties of the surface(s) that guide them.

Generally, the Lamb wave propagations in non-homogeneous composite plates are more complex than in homogeneous isotropic plates due to the anisotropic material properties. In a typical anisotropic composite plate, the material properties depend on the fiber and matrix properties, the fiber orientation, the lamina thickness and the arrangements in the plate thickness direction.

There are two approaches to theoretically calculate the dispersion curves for composite plates; exact and approximate solution approaches [121]. The exact solution consists of applying the 3D elasticity theory and solving the problem by using the matrix methods [122-124]. That means by utlizing the transfer matrix and the global matrix methods. These formulations give a matrix description of the layered plates in terms of the stresses and the displacements along the free surface, and in terms of the incoming and the outgoing wave amplitudes.

For the approximate solutions, the FEM has been used to obtain the dispersion curves for general shaped waveguides. In anisotropic composite plates, homogenized material properties are used at each material layer within the plates.

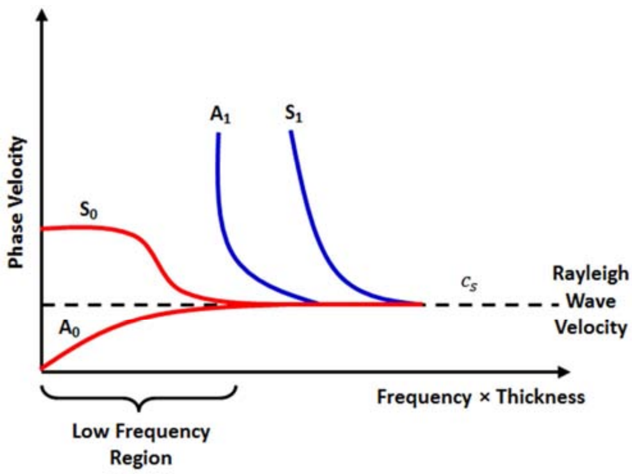
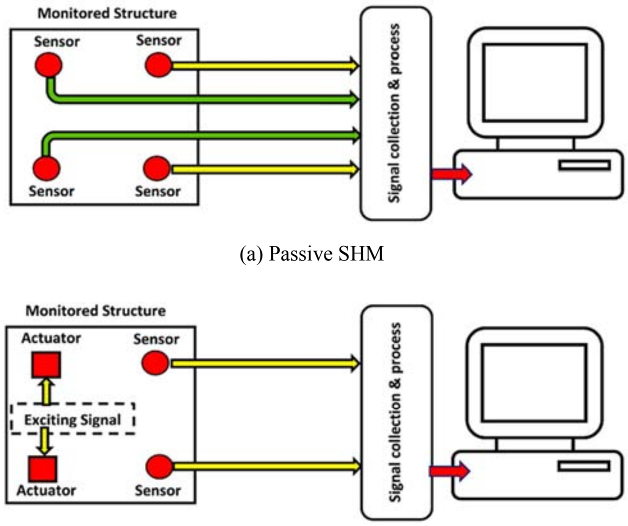


Figure 7. Lamb wave phase velocity dispersion curve for Composite plate.

3.3. Application of Lamb Wave in SHM

Two different types of Lamb waves are used in Structural Health Monitoring (SHM) systems, a passive system and an active system. In passive SHM systems, only sensors are required to detect the Lamb waves produced due to the occurring damages in the structures. However, in active SHM systems, the Lamb waves are excited into the structures using actuators and then sensed back by sensors with the damage informations embedded within the obtained signals as shown in Figure 8. A passive SHM system deals mainly with the problem of damage localizations. An active SHM system on the other hand gives the opportunity for utilizing certain mode types and frequency ranges, which can help to reduce the complexity in the signal processing for damage detections.

Many types of transducers have been developed and utilized for sensing the Lamb waves in composite structures, among them are Ultrasonic transducers [125], Laser transducers [126], Optical fiber transducers [127], Interdigital/Comb transducers [128], and Speckle Interferometry [129]. The Piezoelectric transducers (PZTs) are the most commonly used transducers with Lamb wave technique for fatigue damage detection and localization in composite structures. This is due to high force output at relatively low voltage, negligible mass and volume, simplicity of integration, wide frequency range, low cost and also due to their good response qualities at low frequencies [130, 131].



(a) Passive SHM

(b) Active SHM

Figure 8. The damage detection in active and passive SHM systems.

3.4. Lamb Wave Damage Detection Process

The most suitable method for Lamb wave based damage detection must be able to account for noise, structural vibration, and overlapping of multiple modes. Currently, there are three most commonly used methods of detection. Based on the nature of the signal processing approach we can divide them to time domain analysis [132], frequency domain analysis [133], and time-frequency domain analysis [134]. In most cases of fatigue damage detection of composite structures with Lamb wave technique, time domain based method in dealing with the wave signal is most suitable. By using time domain methods, damage is estimated by using time histories of the input and we can detect damage events easier both globally and locally.

The strategy for damage detection in time domain analysis of the wave signals is based on the cross correlations with the baseline measurement data used for fabricating the signal (no damage conditions). This baseline data is used to subtract the boundary effects from the wave signals (damage conditions), as shown in Figure 9. However, such baseline data are difficult to maintain and change with the environmental conditions.

Two methods of detection, based on time domain method, include direct time and time reversal methods. In direct time domain method, a time series signal normally records the propagation history of Lamb waves travelling in a structure, in order to provide the most straight forward information about the waves (see Figure 9), such as the existence of various wave modes, propagation velocity, attenuation and dispersion with distance, scattering from a structural boundary or damage. The concept of using a Time Reversal Method (TRM) was first used as a means to compensate for the dispersion of Lamb waves, but has recently been applied to diagnose the damage. The advantage of using a TRM, over traditional methods, is that a baseline database is not necessary [135]. This could help minimize false positive damage alerts due to the changes in the environmental and operational conditions. Currently, the TRM has been successfully implemented to detect the presence and the location of damage and has the potential to determine the extent and the type of damage.

Figure 10 illustrates a thorough description of the TRM method for damage detection processes. As can be seen, a transducer array is setup on the structure and a signal is actuated from one transducer and recorded at another.

Each transducer must work both as a sensor and an actuator, therefore, typically Piezoelectric (PZT) transducers are used. The time reversal processes, according to Figure 10, starts with the actuated signal sent from PZT A and recorded at PZT B. The received signal at PZT B is reversed in time (i.e., $V_B(t) \rightarrow V_B(-t)$), and then sent from PZT B back to PZT A where it is recorded, finally, the received signal at PZT A is time reversed and compared to the original signal.

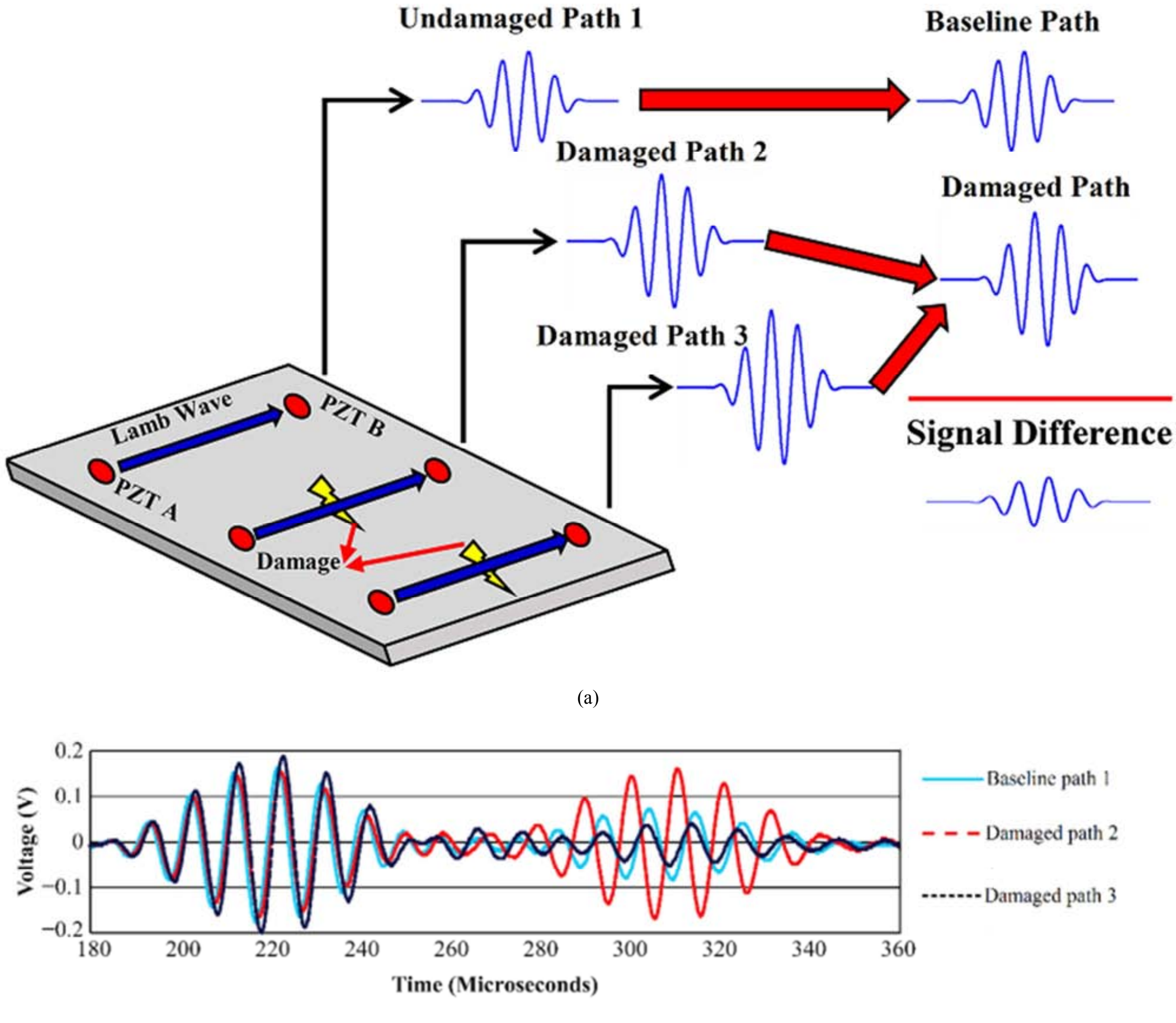


Figure 9. (a) Baseline data SHM Method using Lamb Waves, (b) Lamb wave signals on fabric Plate (Baseline) path 1 and changing the damage Path 2& Path 3

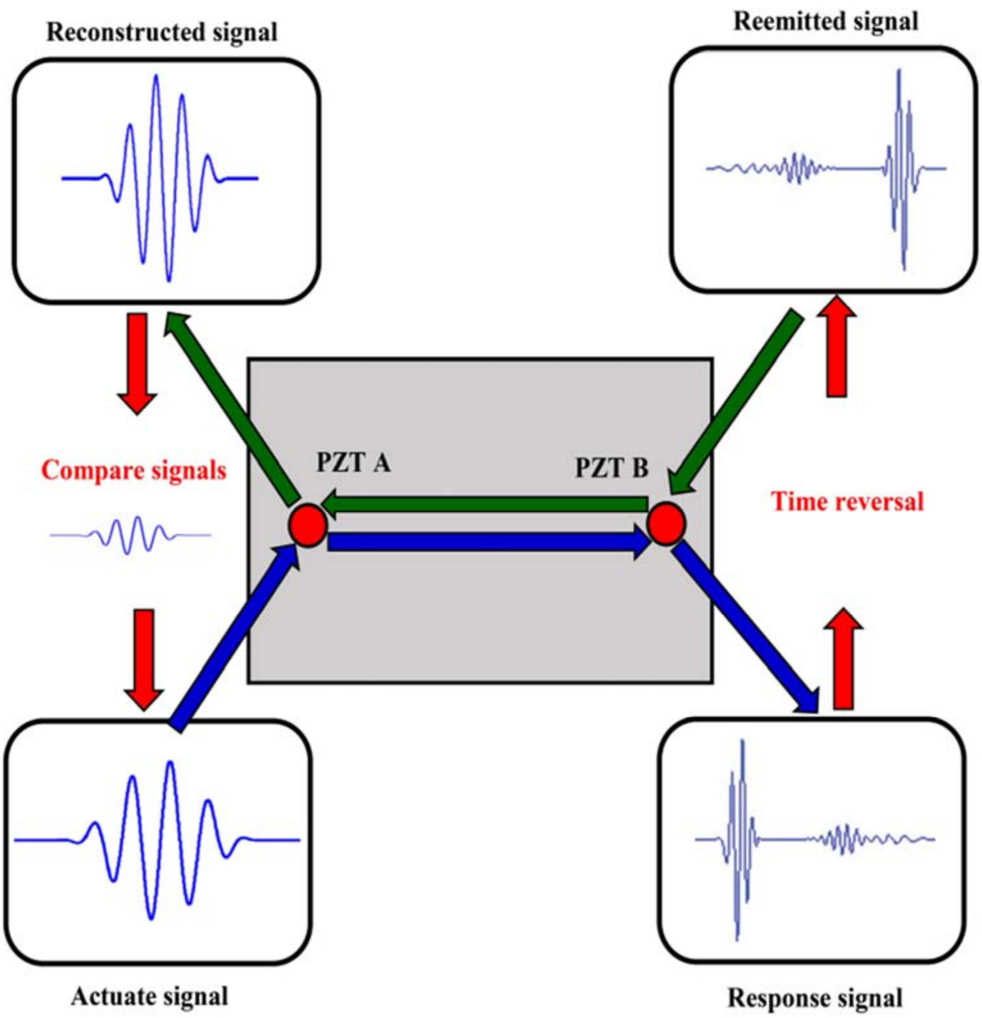


Figure 10. Time reversal processes.

3.5. Damage Localization

Damages can be located using the triangulation method [136], the tomography techniques [137] and the time reversal method [138]. Another approach which is computationally intensive is the utilization of artificial neural network methods [139]. Extensive damage data simulations are needed to train the neural network algorithm on how to locate the damages. However, the algorithm will not be effective if the training conditions change. Damage localizations can also be based on the energy propagation of the Lamb waves [140].

4. Fatigue Damage Prediction with Neural Networks (NNs)

4.1. Introduction

Artificial Neural Network (ANN) is a technique in artificial intelligence, like expert systems, genetic algorithms, fuzzy logics, machine learnings, and Bayesian networks. ANN simulates the function of a biological brain and has been widely used in different research areas such as computer sciences [141, 142] medicine [143, 144] finance [145, 146] social sciences [147, 148] and engineering [149-152]. ANNs have been successfully implemented in numerous applications, e.g. speech recognition [153-155] diagnosis of hepatitis [156] recovery of telecommunications from faulty software [157] image recognition [158-160] and detection of failures in laminated composite materials [164-173].

The popularity and the success of ANN in modeling non-linear problems and its robustness for noisy environment makes them an ideal choice for such kind of applications [140, 161- 162].

ANN is capable of extracting patterns and detecting trends from complicated or imprecise data that are too complex to be analyzed by other diagnosis techniques.

There are numerous different architectures, training procedures, and testing procedures for ANNs. However, in general, an ANN consists of potentially large number of simple processing elements known as nodes or neurons. A neuron influences the behavior of other neurons through a weight. Each neuron simply computes a nonlinear weighted sum of its inputs, and transmits the result over its outgoing connections to other neurons [163]. The behavior of the network depends largely on the interaction between these neurons. The network consists of several layers of neurons. These are input layers, hidden layer or layers, and output layers as shown in Figure 11. The input layer takes the input data and distributes them to the hidden layer(s). The user cannot see any of the input or output of a hidden layer. The hidden layers do all the necessary computations and transmit the results to the output layer, which provides the final result to the user.

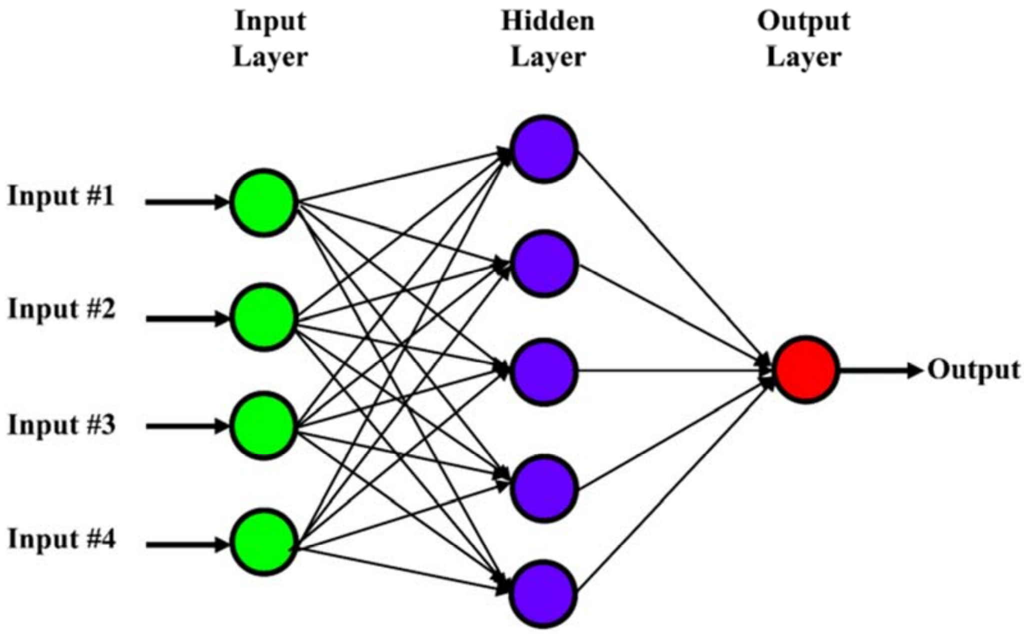


Figure 11. A simple neural network with 3 layers (input, hidden, and output).

4.2. Damage Detection and Location in Composites

The use of ANN for the detection of damage detection and its location procedures in SHM of composites was motivated due to the possibility of the existence of different types of damage at several different locations within the same structure, making damage detection a complicated process.

Hanagud and Luo [164] used a three layer feed forward neural networks to identify two different types of damage in glass fiber reinforced polymers (GFRP) delamination and stiffness reduction, due to transverse cracks or impact damage. It was assumed that only one of these defects existed, and analytical models were built to predict the dynamic behavior of the structure considering various scenarios of damage. In their work, the main neural-network identified the type of existing damage using a non-linear dynamic response criterion, which directs the problem to one of two sub-networks. Both these sub-networks used Frequency Response Function (FRFs) as inputs. Using the same beam as a "case study", Luo and Hanagud [165] proposed the Dynamic learning rate Steepest Descent (DSD) for training neural networks, with the aim of increasing the learning convergence speed relative to the simple steepest descent method.

Krawczuk et al. [166] presented the results of the application of a genetic algorithm and a neural network for the detection of damage and location of delamination in a numerical model of a multi-layered GFRP beam. Two different procedures were followed to identify the damage location and size: the first was based on FE model updating and error location, while the second considered a set of possible damage scenarios, including damage type, location and size. These authors used an objective function, based on changes in the first four natural frequencies, and on the Dynamic Learning as proposed by Messina et al. [167]. In that work, the genetic algorithm converges after a reasonable number of iterations. However, these authors concluded that theirs procedure deserved future development by including more processes that are observed in nature, for example elitism. It appears that in the work presented by these authors, the neural network's performance in detecting the delaminated layer location across the thickness was poor possibly because they considered a relatively small population of delaminated cases for training.

Hatem et al. [168] also applied genetic algorithms and neural networks to damage detection in Carbon Fiber Composites (CFRP). Four types of damage were considered in the model of a cantilevered beam: circular holes (with different diameters and locations), delaminations (with different areas and locations), linear surface cracks (with different lengths, orientations and locations), and linear through cracks (with different lengths, orientations and locations). Damage type was identified by the generalized regression network. A special sub-network was used for each damage type, in an ensemble of five: a generalized regression network, a linear network, two back-propagation networks (with and without regularization) and a radial basis network. These authors stated that the generalized regression networks successfully classified the damage type, with a success rate ranging from 85% to 98%. In the aforementioned work, after the damage is classified, an appropriate neural network or genetic algorithm is run to detect the remaining damage parameters, namely the location, size and, in the case of a crack, its orientation. Damage size was predicted with good accuracy, but the results on damage position and orientation were not highly accurate.

Zheng et al. [169] combined computational mechanics and neural networks. In their study the back-propagation method was used to predict the delamination in CFRP beams. The neural network was trained with FE models, which were designed assuming various delamination sizes and locations. As inputs, the model used the first five natural frequencies. According to these researchers, the neural network correctly predicted delamination size and location within a small error margin.

Haj-Ali et al. [170] proposed the use of ANN to generate nonlinear micromechanical ANN models. The interfacial crack between the fiber and the matrix was considered as the damage variable. The crack angle was used as a damage parameter in the unit cell (UC) models for a unidirectional metal–matrix composite. ANN models were trained to generate plane stress strain constitutive models along with their damage variable using 3D FE simulation results. The study was one of the first to show that ANN could be used to generate micromechanical material models with damage. However, their ANN was limited to monotonic behavior and for a specific system of boron–aluminium metal matrix composite material.

Chakraborty [171] embedded delaminations, in terms of their size, shape and location, in fiber reinforced plastic composite laminates and they carried an investigation using natural frequencies as the indicative parameters and an artificial neural network as a learning tool. Numerical simulations were used to generate the data set. Various configurations of embedded delaminations in the FRP composite plate were modelled and three-dimensional finite element analyses were performed to extract the first 10 natural frequencies. In their research, a total of 201 FE models, with different combinations of delamination size, shape and location, were run and 201 data sets generated.

The results were normalized between 0.1 and 0.9. A total of 165 data sets were chosen at random for the purpose of training the network and the rest were reserved for testing.

Roseiro et al [172] proposed a neural network based methodology to identify and quantify damage using data obtained from piezoelectric sensors as inputs to a feed forward neural network (FFNN). They used a higher order finite element formulation allowing the response of the laminated composite plates to obtain the necessary electrical potential on sensors. Then they used a numerical example of a simply supported laminated composite plate to show the feasibility of the method.

Karnik et al [173] analyzed the delamination behavior as a function of drilling process. Parameters considered were related to the initial penetration of the drill in the CFRP plates. The delamination analysis due to high-speed drilling was performed by an artificial neural network (ANN) model with spindle speed, feed rate and point angle as the affecting parameters. A multilayer feed forward artificial neural network, trained using an error-back-propagation training algorithm (EBPTA), was employed for this purpose.

Al-Tabey [6] designed an expert system to expect the number of cycles to failure (N) for woven-roving glass fiber reinforced epoxy (GFRE) with [0,90°]3s and [±45°]3s fiber orientations under combined bending moments and internal hydrostatic pressure. Three ANN architectures were investigated: the feed-forward NN (FFNN), a generalized regression NN (GRNN) and Radial basis NN (RBNN) to predict N for pressure ratios between the applied and burst pressure Pr = 0.25, 0.5 and 0.75. He then compared the results of ANNs with the experimental results, Ultimately, he concluded that the trained FFNN demonstrated the best results to expect with pressure ratios 0.3, 0.6 and 0.9 and random values of maximum normal stresses. He further found that the FFNN Artificial Neural Network was suitable and useful in predicting non-experimental data generated by the computational model.

Altabey and Noori [174] used different significant parameters as the sole input to two different neural network (NNs), a feed-forward neural network (FFNN) and a Radial Basis neural network (RBNN), are applied, trained and tested, in order to predict the fatigue life in carbon fiber/epoxy laminate composites subjected to spectrum loading. Different negative and positive stress ratios are considered and the residual strength effect from spectrum loading is taken into account, by applying the two-parameter Weibull probability density distribution.

Zhao et al [175] presented a comprehensive reliability evaluation framework for a laminate composite plate under hydrostatic pressure. They conducted an establishment and verification of a response surface, the determination of performance function in terms of input and output random variables, and the comparative application of combined algorithms such as Monte Carlo simulation, artificial neural network and fuzzy theory. They found that the Back Propagation based artificial neural network can be used as a substitute for the mapping relationship of the input and output of the performance function, and this validate its advantage over JC method and Markov Chain Simulation.

5. Conclusions

In this work we discussed an overview of Lamb waves characteristics, modeling and applications, as well as the limitations for fatigue damage detection of composite structures. This study consisted of three parts:

First, an overview of composite materials and composite structures, including the failure mechanisms, behavior of composite materials under fatigue loading and what parameters affect the fatigue damage was presented. As discussed, during the fatigue process, damage starts at an early stage, subsequently it evolves through three phases that eventually lead to failure. These phases include: matrix cracking (phase I), development of local delaminations caused by matrix cracks (phase II), and consolidation of local delamination leading to final failure (phase III). These phases lead to categorizing the fatigue behavior of composite materials to three regions, depending on the fiber, matrix, and interface properties. As presented in the fatigue life diagram (FLD) in Figure 4. there are several factors that influence the fatigue life diagram (FLD) of composites: Loading types; Loading frequency; Volume fraction (Vf); Fiber orientation; Mean stress and stress ratio; Environmental factors; Sizing and stress gradient; Surface finish; and Stress concentration.

In the second part of this work we discussed how to detect the fatigue damage presented in the part 1. Several non-destructive testing (NDT) methods were discussed, each with different sensitivities and capabilities. These methods, which have advantages and limitation for damage identification of laminate composite structures include: Ultrasonic; X-Ray Radiography; Thermography; Acoustic Emission; Vibrography; Eddy Currents; Optical Fiber Sensors, and Lamb Wave. The applicability of each method in damage detection and location were listed in Table 1. As concluded and discussed, the damage identification techniques using Lamb waves are envisioned to be promising methods in lieu of traditional NDE approaches because of the following characteristics of Lamb waves:

(1) The capacity to inspect a large area using few transducers in a sparse configuration. It has been decreased the ratio of the area lost in the plate area (the area of transducer wave non-propagation) to the area of a transducer wave propagation depend on the location of the transducers distributions;

(2) The ability to inspect the cross-sectional area along the length of the structure in terms of multiple wave modes, thereby detecting internal damage as well as surface defects. Also, the capability of classifying various types of damage using different wave modes.

(3) High sensitivity to damage and therefore, high detection accuracy.

(4) The possibility for integration by designing structures with proper communication for developing between online automated damage detection and SHM techniques to decrease the energy consumption with great cost-effectiveness; but the complicated signal appearance, this requiring well calibrated signal processing and computing techniques.

(5) Lamb waves technique display great capabilities in detecting the damage location in composite structures especially using different methods of Artificial Neural Networks (ANNs) in order to suitable different damage type.

(6) Finally, this paper discussed and demonstrated that the Lamb wave method is highly sensitive and more accurate in evaluating damage detection and location than other techniques.

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