CHAPTER 2

LITERATURE REVIEW/THEORETICAL BACKGROUND

Recent works in the field application of NN for predicting fatigue life of composite are elaborately presented in this chapter. It is followed by brief discussion of the important aspects related to composite and fatigue loading of constant amplitude (CA). The concept of CA is then extended to variable amplitude (VA) by introducing the constant life diagrams (CLD) as an extension of *S-N* curve. For the purpose of fatigue life assessment under VA loading, the usefulness of CLD is also discussed. It can be seen that the definition of limited set of stress ratios found its concept from the CLD.

2.1 Fatigue Life Assessment of Composite Materials Using NN

In this last decade, researchers in fatigue field have explored NN as an information processing and computing tool to deal with fatigue related problems [2, 3, 19]. The use of NN has also been a new route in fatigue life assessment where the aim is to develop NN model(s) that produce reliable prediction using a limited body of fatigue data. Evidently, this will give great advantage in particular for design engineers in their design phase and plans. The characteristic of NN that can be taught to emulate relationships in sets of data to subsequently predict the outcome of another new set of input data, for example another composite system or a different stress environment, is exploited.

The use of NN in fatigue life assessment of composite materials has a wide range of applications from unidirectional [2, 20, 21] to multidirectional laminate [3, 22-24]. The comprehensive review for the works forms as motivation leading to the current research work presented in this thesis.

Aymerich and Serra [2] performed NN prediction of fatigue strength in relation to types of stacking sequence and lamina orientation within laminates. The composite under consideration was carbon fiber reinforced polyether ether ketone (APC-2) with various stacking sequences: $[0]_{8s}$, $[+15/-15]_{4s}$, $[+25/-25]_{4s}$, $[+35/-35]_{4s}$, $[+45/-45]_{4s}$, $[0/90]_{4s}$ and $[-22.5/22.5/-67.5/67.5]_{4s}$ (refer to 2.1.2.1 for laminate coding). The number of cycles to failure and an orientation angle or a set of orientation angles identifying the stacking sequence of the laminate were used as the input parameters of their NN model. Meanwhile the output was the associated fatigue strength. The number of hidden neurons varying between 4 and 12 was utilized. The researchers pointed out that neural networks were potentially able to predict fatigue life of fiber-reinforced laminates provided that a sufficiently large set of experimental data, representative of the characteristic damage modes of the category of examined sequences, is available. Nevertheless, further investigations are needed to establish empirical concerning limits and confidence levels of fatigue life predictions by neural networks and to aid in the identification of suitable learning sets.

Lee and Almond [3] predicted the fatigue lives of carbon/glass fiber reinforced plastic (CFRP/GFRP) laminates using NN. Four CFRPs, namely HTA/913, T800/5245, T800/924 and IM7/977, all with $[(\pm 45,0_2)_2]_S$ lay-up, were examined to evaluate possible NN architectures and training methods to be used for the networks. In the study, the authors pointed out that the training base for NN should be constructed from monotonic properties such as tensile strength and compression strength and fatigue related data such as maximum stress, minimum stress or amplitude stress. In addition, the fatigue database used as training set should include values from three stress ratios-R, for example: R = 0.1, R = -0.3 and R = 10. Also, the lay-up of the specimens should be the same for all the evaluated materials. Finally, they did not recommend the use of CFRP fatigue lives to predict the fatigue lives of GFRP or vice versa, because the differences in the mechanical properties and fatigue responses of the materials.

Al-Assaf and El-Kadi [19], and El-Kadi and Al-Assaf [20] assessed the fatigue life of unidirectional glass fiber/epoxy laminae using different neural network paradigms, namely feed forward (FF), modular (MN), radial basis function (RBF) and principal component analysis (PCA) networks, and compared the prediction results to the experimental data. The tested specimens had five fiber angle orientations of 0°, 19°, 45°, 71° and 90° were tested under three stress ratios-R of -1, 0 and 0.5. Ninety two experiment data made up the application data for the networks. They found that NN can be trained to model the nonlinear behavior of composite laminate subjected to cyclic loading and the prediction results were comparable to other current fatigue life prediction methods. In addition, the authors noticed that the predictions obtained using

FF and MN were superior to those obtained using other networks. Nevertheless, only three stress ratios-*R* were investigated and large discrepancies to the experimental data were still found.

Freire Junior et al. [21] followed different approach, by which NN was utilized to build constant life diagrams (CLD) of fatigue. The CLD is a very useful tool in fatigue life assessment under variable amplitude loading, where all points with the same fatigue life are connected with lines in a plane of amplitude stress (σ_a) - mean stress (σ_m) axes. Figure 2-1 shows the schematic of CLD.

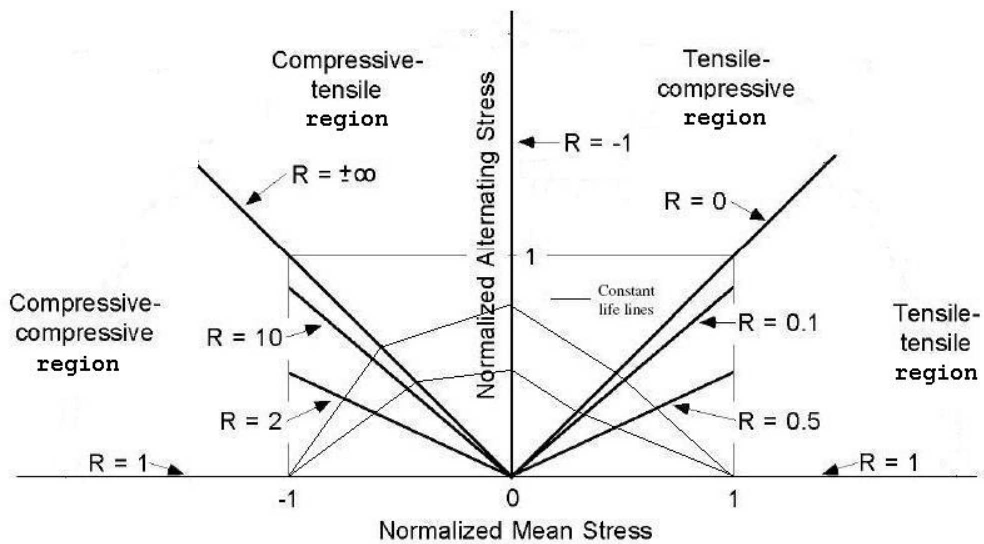

Figure 2-1 A schematic representation of CLD.

The researchers built CLD of a plastic reinforced with fiberglass (DD16 material) with $[90/0/\pm45/0]_S$ lay-up. Having *S-N* curves of the material from twelve stress ratios-*R*, four training data sets (each set consists of 3*R*, 4*R*, 5*R* and 6*R* values, respectively) were set up. It is interesting that the mean stress and fatigue life values were used as input set, while the amplitude stress was the output (not directly assessing fatigue life). The training algorithm was the standard backpropagation with 8, 23, 11 and 23 hidden nodes for each of the training sets. It was found that the use of NN on building CLD was very promising and that the NN trained using only three *S-N* curves could generalize and construct other remaining *S-N* curves of the CLD building. However, it was also pointed out that six *S-N* curves should be utilized in NN training for better generalization.

Vassilopoulos et al. [22] criticized that the determination of six *S-N* curves was a costly task for the NN prediction purpose. Instead, these authors used a small portion of the experimental data (that is only 40% of fatigue life data, but each of stress ratios has its representatives) when assessing fatigue lives of GFRP laminate of $[0/(\pm45)_2/0]_T$ and GFRP laminate of $[90/0/\pm45/0]_S$ with four and five stress ratios-*R* values, respectively. It was shown that it is possible to build CLD for both material systems using the small portion data and that NN was proven to be a sufficient tool for modeling fatigue life of GFRP multidirectional laminates. However, the researchers also stated that one of the NN major unresolved problems was the weakness of extrapolating model's predictions outside the training set region. Therefore, a different network is currently under examination by the authors.

In their next paper, Freire Junior et al. [23] showed that the use of modular networks (MN) gives more satisfactory results than feed-forward (FF) neural network. However, it was still necessary to increase the training sets for better results. As the last review, Zhang and Friedrich [24] stated that fatigue behavior is still so complicated that the problem requires more effort before NN can be used with more confidence.

From the recent investigations, it can be concluded that NN is proven to be a sufficient tool for modeling fatigue life of composite materials, ranging from unidirectional to multidirectional laminate. In addition, NN also shows the potential for fatigue life assessment under variable amplitude loading. Nevertheless, there is still the need for further study and investigation, in particular to extend and validate the NN prediction capability on predicting fatigue lives of stress ratios-*R* apart from the ones used in the training set or beyond the range of data on which NN was trained. The current study is closely related to the latest works of [19-21] and intended to build an efficient NN model utilising less training data set than previous works, where at least three stress ratios-*R* were utilized to obtain reasonable fatigue life predictions.

To improve NN performance, the weights initialization and set of inputs selection could be optimized. These will lead to an efficient and effective NN learning towards the desired output. The NN structure could be enhanced through network pruning/growing or hybrid models such as neuro-fuzzy model and neural networks-genetic algorithms. The use of nonlinear optimization techniques such as the Levenberg-Marquardt and nonlinear conjugate gradient methods or through hybrid training algorithm could be incorporated in the standard backpropagation algorithm to improve its performance.

2.2 Composites

Generally, composite refers to a material consisting of two or more components with different properties and distinct boundaries on macroscopic scale. Usually, one component acts as load carrying reinforment, one component acts as a matrix or binder transfering external load to the reinforment and another component is an interface between the matrix and the reinforment.

Further, based on the reinforment form, composites can be classified into two groups, namely fiber composites and particulate composites. Fiber reinforced composites are considered as advanced composite materials and mostly used in modern applications. Meanwhile, particulate based composites, like other conventional materials such as metal and aluminum alloys, can be treated as homogeneous and isotropic materials [25]. Figure 2-2 describes the formation of composites and their classifications.

An important feature of the fiber reinforced composites is their ability to be designed according to their application and performance requirements. For example, composite laminate can be tailored to have the desired strength along the preferred direction by particular arrangement of the lamina or composite materials can be designed to have high ratio of strength/stiffness to density properties [25]. More recently, fiber composites have been designed to become “smart or intelligent” composites by embedding sensor devices in them [26].

In the context of fatigue resistance, composites have excellent fatigue strength up to 90% of their static strength, especially for unidirectional laminate, compared to 50% of the static strength for steels and titanium alloys and 35% of the static strength for aluminum [27].

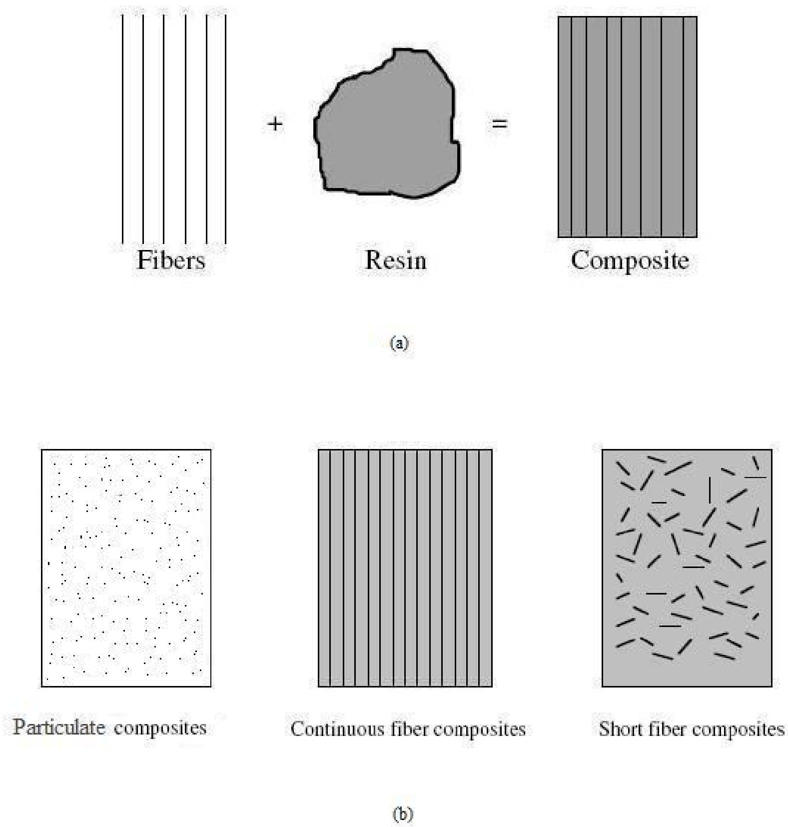

Figure 2-2 (a) Formation of a composite material from fibers and resin. (b) Types of composites.

2.2.1 Fiber and Matrix

Fiber and matrix play important role in a composite material. Various types of fiber and matrix can be chosen to form composites with particular mechanical and environmental properties as stated in the previous section. The characteristics of composite materials, therefore, depend on three main factors, namely the proportion of fiber and matrix, the fiber form (including lay-up) and the fabrication process. Table 2-1 summarises the functions of fiber and matrix in composites.

Table 2-1 The functions of fiber and matrix in a composite

Component	Functions
Fiber	Carrying load (70 – 90% of load is carried by fibers)
	Providing stiffness, strength, thermal stability and other structural properties
	Providing electrical conductivity or insulation, depending on the fiber used
Matrix	Binding fibers together and transfering load to the fibers
	Providing ductility, toughness (especially thermoplastic based composites) and impact strength properties
	Providing protection to fibers againts chemical & environmental attack and mechanical damage (wear)
	Isolating fibers and slowing crack propagation
	Providing a good surface finish quality, compatibility with fibers and elasticity in the production of net-shape

As shown in Figure 2-2(b), fibers can be in the form of short and long (continuous) fibers. Short fibers have length of a few centimeters or fractions of milimeters (chopped fibers) and used in compression and injection molding. Meanwhile, long fibers are in the form of continuous fibers as used in unidirectional or woven form.

For matrix, three different types are possible, polymeric, metallic and ceramic matrices. Polymeric matrix, includes thermoset resins (epoxies, polyesters, polyurethanes, phenolics, melamines, silicones) and thermoplastic resins (polyetheretherketone, polypropylene, polyamide, polyphenylene, sulfone). Metallic matrix, includes aluminum and titanium alloys and copper. Ceramic matrix, includes carbon, silicon carbide and silicon nitride. Ceramic based composites exhibit very high temperature resistance of greater than 2000°C.

2.2.2 Laminated Composite

In structural forms, composites are made of layers of ply or lamina bonded together to form a laminate. A ply or lamina may consist of short fibers, unidirectional continuous fibers or woven (braided) fibers embedded in a matrix. A ply containing woven fibers is referred to as fabric. Lamina is therefore a basic building entity of composite laminate.

Further, adjacent plies having the same material and orientation are referred to as a ply group, and a ply group may be treated as one layer. In general, a composite laminate can be composed of ply, fabric, ply groups and/or layers. Figure 2-3 shows lamina as a basic building entity of composite laminate and laminated composite.

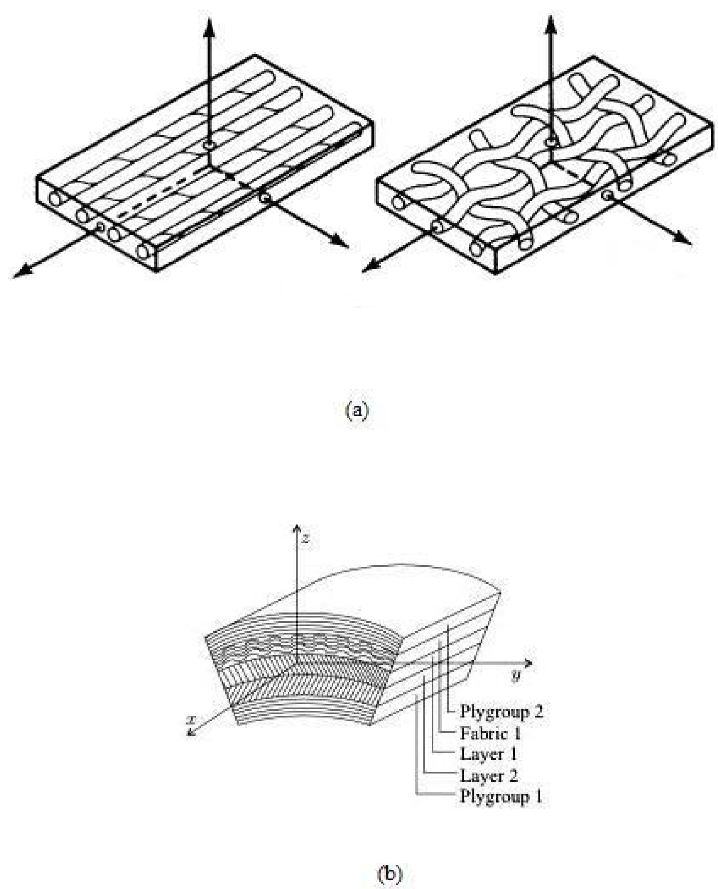

Figure 2-3 (a) Lamina as a basic building entity of laminate, in the form of unidirectional and braided. (b) A laminated composite.

2.2.2.1 Laminate Code

A laminate code defines how plies are arranged or laid up in a laminate. The composite lay-up is then named according to the code.

An x, y, z orthogonal global coordinate system is used in defining laminate designation with z being taken perpendicular to the plane of the laminate as illustrated in Figure 2-4. The orientation of continuous, unidirectional plies are specified by the angle θ (in degree) with respect to x-axis. Positive θ is in the counterclockwise (CCW) direction and a numerical subscript indicates the number of plies within a ply group. Stacking plies in a laminate is in the z-positive direction. Stacking sequence of a laminated composite starts from bottom to top as shown in Figure 2-5.

For example, a lay-up of $[45_3/0_4/90_2/60]_T$. There are four ply groups. The first, the second, the third and the fourth ply contains three plies in the 45-degree, four plies in the 0-degree, two plies in the 90-degree and one ply in the 60-degree direction, respectively, CCW from the x-axis.

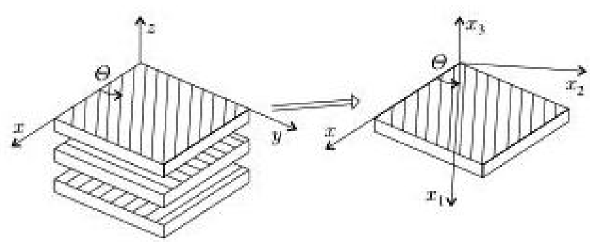

Figure 2-4 The x, y, z laminate (global) coordinate system, the x_1, x_2, x_3 ply (local) coordinate system and the ply angle θ.

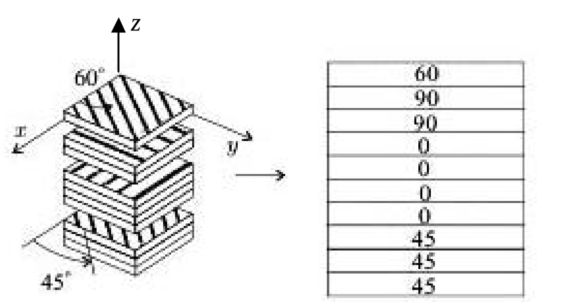

Figure 2-5 Stacking sequence description of $[45_3/0_4/90_2/60]$ lay-up.

A laminate is said to be a symmetric laminate if it is symmetrical with respect to a mid-plane in the stacking sequence. A symmetric laminate is indicated by subscript S referring to symmetric. If the symmetry is in reversed sequence, the laminate is said as antisymmetric. Otherwise, the laminate is unsymmetric. An unsymmetric laminate is indicated by subcript T referring to total. In practice, however, the subscript T is often omitted. For example $[-45_2/0_4/-45_2]$ is a symmetric laminate, then its code can be reduced to $[-45_2/0_2]_S$. Meanwhile $[-45_2/0_2/-45_2/0_2]$ is an antisymmetric laminate.

2.2.2.2 Special Laminates

Special laminates are laminates that have optimized stacking sequences to yield desired elastic behaviour and design strength. There are four types of special laminates.

The first is a balanced laminate. In balanced laminates, for every ply with $+\theta$ direction, there is an identical ply with $-\theta$ direction. For example: $[45_2/90_2/60/-60/-90_2/-45_2]$, $[45/-45/75/-75]_S$.

The second is an angle-ply laminate. Angle-ply laminates consist of only plies with $+\theta$ and $-\theta$ directions. Angle-ply laminates may be symmetric or unsymmetric, balanced or unbalanced. For example: $[-22.5_2/22.5_2]_S$, $[-45_2/45_2/-45_2]$.

The third is a cross-ply laminate. Cross-ply laminates have plies with 0- and 90-degree directions only. Cross-ply laminates are balanced and may be symmetric or unsymmetric. For example: $[0_4/90_4]$, $[0_2/90_2]_S$.

The fourth is a quasi-isotropic laminate (QI). All symmetric laminates with Z equal angles of 180°/Z, where $Z \geq 3$, between fiber orientations are quasi-isotropic (QI) laminates. The laminates are called quasi-isotropic because their elastic behaviour under in-plane loading is like the one of isotropic materials. An example of QI laminate being used in the aerospace industry is $[0/45/90/-45]_S$ laminate.

Advanced discussion and mechanics of laminate can be found in [25, 28].

2.3 Fatigue of Composite Materials

It is a routine task done by design engineers to estimate the lifetime of a component or structure under long-term fatigue loading influence to ensure good reliability during its service. Moreover, 50-90% of component failures are due to fatigue [29]. Therefore, it is crucial to understand about fatigue and how a component or structure behaves if it is subjected to fatigue loading.

2.3.1 Fatigue

Fatigue is defined as a material failure that is caused by repeated loadings or block-loadings, whether at constant amplitude or variable amplitude. Fatigue degrades the quality of material and eventually causes material failure, although the applied loads, in terms of stresses, strain or energy, may be much lower than the static strength values of the material itself.

In composite applications, the inhomogeneous and anisotropy characteristics of composite materials require fatigue evaluation, where the fatigue behaviour of the composites in response to long-term loading condition is determined. Due to the nature of composites, the following factors must be considered in the evaluation. Fibre and matrix types, volume fraction of reinforcement, reinforcement structure types (unidirectional, fabric, braiding, mat), fibre orientation and laminate stacking sequence and moisture which could result in hygro-thermal strains or stresses. In addition, the presence of notch, adhesion, joints and any other stress concentrators in a composite structure must also be considered in the evaluation.

There are a number of differences between the fatigue behaviour of metals and composite materials. In metals, fatigue damage is represented by single major crack growth until final failure and the stage of the gradual and invisible degradation spans nearly the metal whole lifetime. Also, there is no significant reduction of stiffness during the fatigue process. On the other hand, for composite materials especially fibre-reinforced composite materials, various damage mechanisms can exist such as fibre breakage, fibre buckling, transverse-ply cracking, delamination, debonding and matrix cracking [30]. The damage also begins very early and the presence of a damage could stimulate other types of damage development [31, 32]. The loss of stiffness and strength are also observed during the damage process, leading to a continuous distribution of stresses inside the composite materials. All these force the stress state to change [33] that damage assessment of composite materials becomes more complicated. It is clear that fatigue in composite materials is a complex phenomenon, due to many variables involved, from types of material, loading & environmental conditions and geometric and boundary conditions, that must be taken into account in the fatigue evaluation and analysis.

The ideal approach in predicting the fatigue life of fibre composites would be based on a detailed understanding of the manner of the microstructural damage accumulates as offered by progressive damage models. The models need detailed information about the actual damage mechanisms or quantitatively account for the progression of damage. Another approach is using fatigue damage indicators such as residual stiffness/strength, as given by phenomenological models. With phenomenological models, there is a need for intermittent fatigue test to measure residual strength or to add additional non destructive evaluation (NDE) equipments to measure residual stiffness [1, 32].

The facts have motivated researchers to reduce the burden in obtaining empirical data required in the fatigue evaluation and assessment of composite materials. The efforts have given more attention to stress-life approach that usually being represented by *S-N* curves. The assessment task is then made simpler by just predicting the number of cycles at which fatigue failure occurs under fixed loading conditions. To deal with complex loading situations, then the information in such curves are extracted and transformed into a “master diagram”, which then be utilized to provide insights on predicting fatigue life of a composite material at the complex loading situations.

As mentioned in the previous chapter, recent efforts in fatigue life assessment of composite materials by utilizing stress-life approach have utilized NN modeling as the framework.

2.3.2 Constant Amplitude Loading Fatigue

A constant amplitude fatigue load is generally represented by a cyclic, typically sinusoidal, waveform [34] as shown in Figure 2-6. The fatigue loading at different load regimes or stress ratio R conditions are illustrated in Figure 2-7.

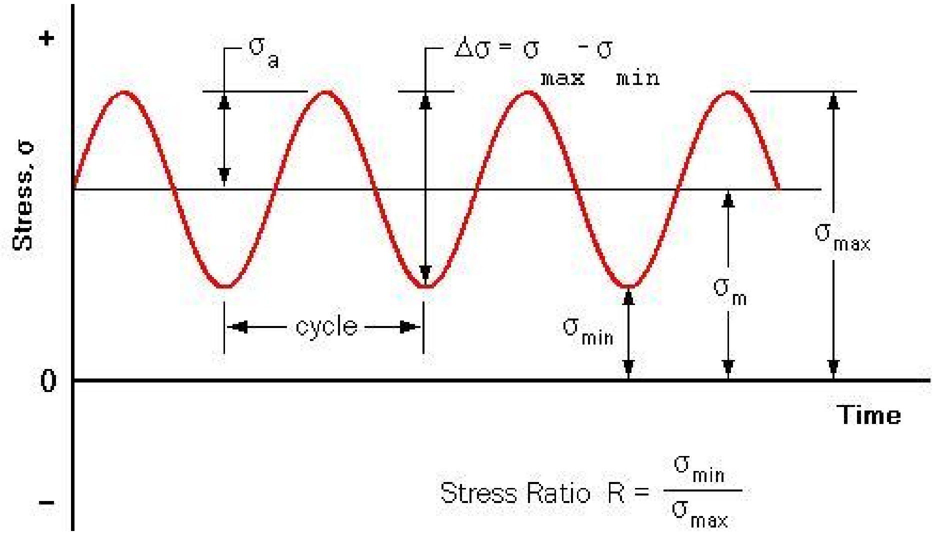

Figure 2-6 Typical constant amplitude cyclic loading waveform and its parameters.

Common terminologies and symbols used in fatigue loading are as follows:

R = $\sigma_{min}/\sigma_{max} \equiv$ stress ratio
σ_{max} (S_{max}) $\equiv$ maximum stress
σ_{min} (S_{min}) $\equiv$ minimum stress
σ_m (S_m) = $(\sigma_{max} + \sigma_{min})/2 \equiv$ mean stress
σ_a (S_a) = $(\sigma_{max} - \sigma_{min})/2 \equiv$ amplitude stress ($\Delta\sigma \equiv$ stress range = $2\sigma_a$)

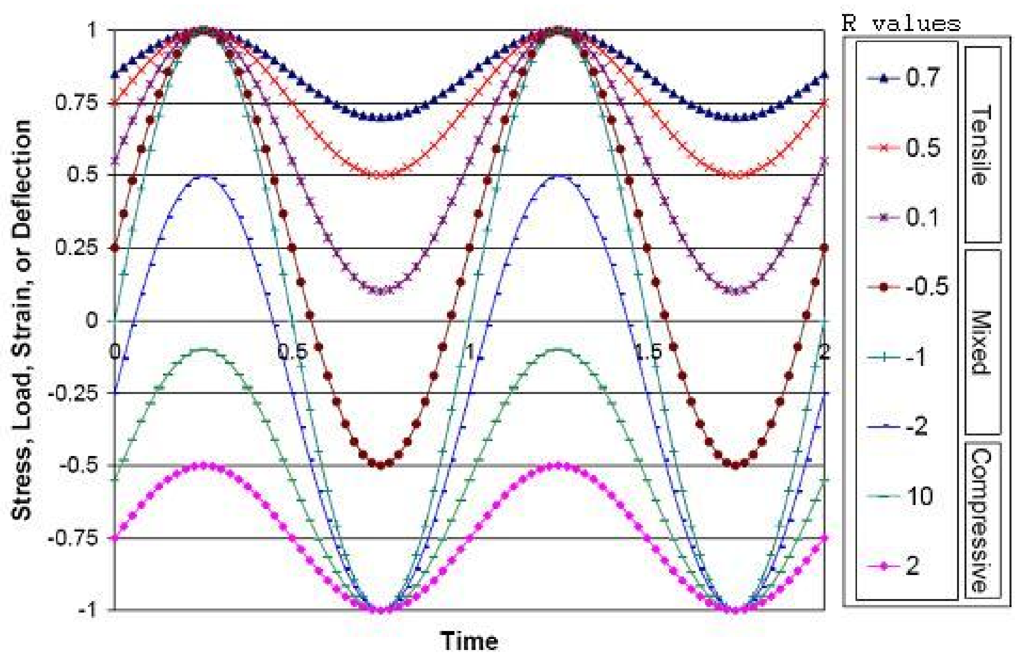

Figure 2-7 Fatigue loadings at different load regimes or stress ratio-*R* conditions.

In its real application, a composite structure is frequently subjected to complex loading patterns of varying amplitude and mean stresses, which can be idealized as superposition of constant amplitude loadings shown in Figure 2-7, rather than constant amplitude loadings along its service life.

However, constant amplitude loading fatigue test has great significance in understanding fatigue phenomena, especially in material testing for three reasons. Firstly, it provides an effective manner to get information on fatigue life (time to failure) as well as fatigue behaviour of a material in terms of how many loading cycles (*N*) the material can withstand at certain stress level (*S*), stress ratio (*R*), loading frequency (ω) as well as specific lay-up. Repeating such a test until the material breaks at different stress levels (fixed *R* and ω) will allow the results to be plotted in the well-known *S-N* diagram.

Secondly, some measures of material degradation such as residual strength *R(N)* and residual stiffness *E(N)* after *N* loading cycles could also be assessed from the test in addition to the obtained fatigue life N_{fail}. Altogether, the measures form the basis for building "fatigue failure criterion" model to estimate a component's or structure's lifetime.

Thirdly, constant amplitude fatigue forms "building blocks" for assessing fatigue life of a material or structure subjected to complex and wide spectrum of fatigue loadings at varying amplitude and mean stresses and history. For instance, CLD constructed based on the *S-N* curves at several stress ratios could be used to assess fatigue life of a material or structure under fatigue loading with varying amplitude and mean stresses (CLD is discussed in 2.3.3).

2.3.2.1 The *S-N* Diagram and Related Formulae

Fatigue test results are usually represented in an *S-N* diagram. Generally, *S* represents load in form of maximum stress, strain amplitude or displacement range, and *N* represents lifetime in terms of cycles to failure or time, as shown in Figure 2-8.

There is a common convention in plotting the test results where fatigue life *N* is plotted as x-axis instead of y-axis, although the fatigue life is actually a dependent variable and the applied stress is independent variable. With the convention, in some *S-N* equations *S* is treated as a dependent variable and placed on the left-hand side of the equations.

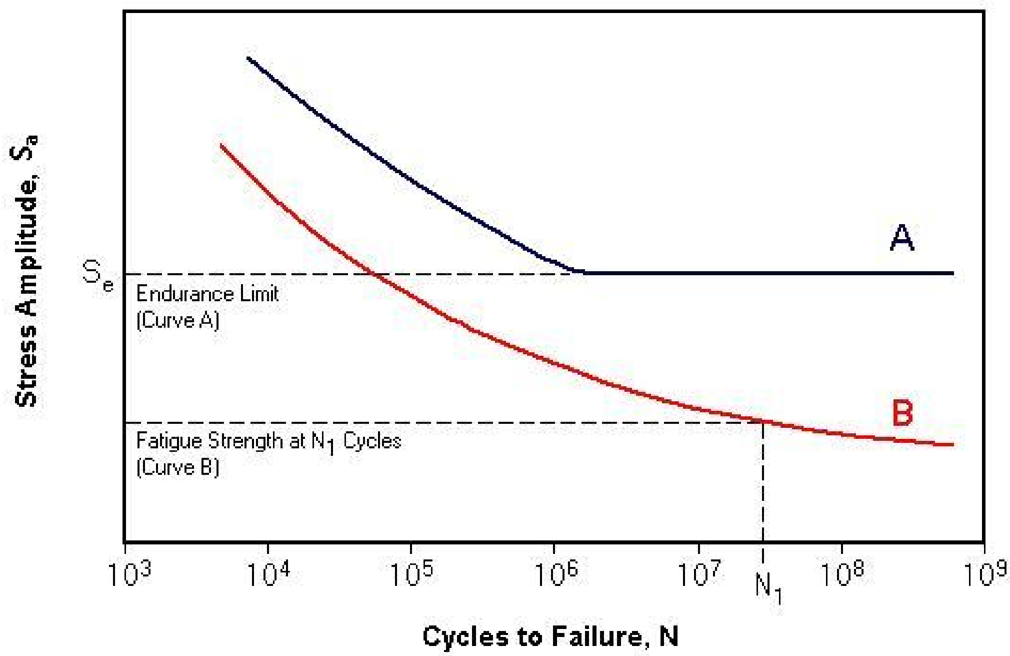

Figure 2-8 Typical *S-N* curves.

Relationship between fatigue life *N* and the applied stress *S* can be mathematically expressed as in Equation (2-1):

$$N = KS^B \tag{2-1}$$

where K is equal to 10^A.

Commonly, the logarithm of constant amplitude fatigue life *N* is assumed to be in linear relationship with the applied stress *S* or its logarithm as in Equation (2-2) and (2-3):

$$\log N = A + B.\log S \tag{2-2}$$

$$\log N = C + D.S \tag{2-3}$$

where:

N	≡ fatigue life
S	≡ applied stress
A, B, C, D	≡ constants, depend on fatigue stress state at specific R value

Equation (2-2) is called a log-log or power law formula and equation (2-3) is called a lin-log or semi-logarithmic formula.

Figure 2-9 shows S-N curves on semi-log plot fitted to fatigue data taken from [40] using various equations.

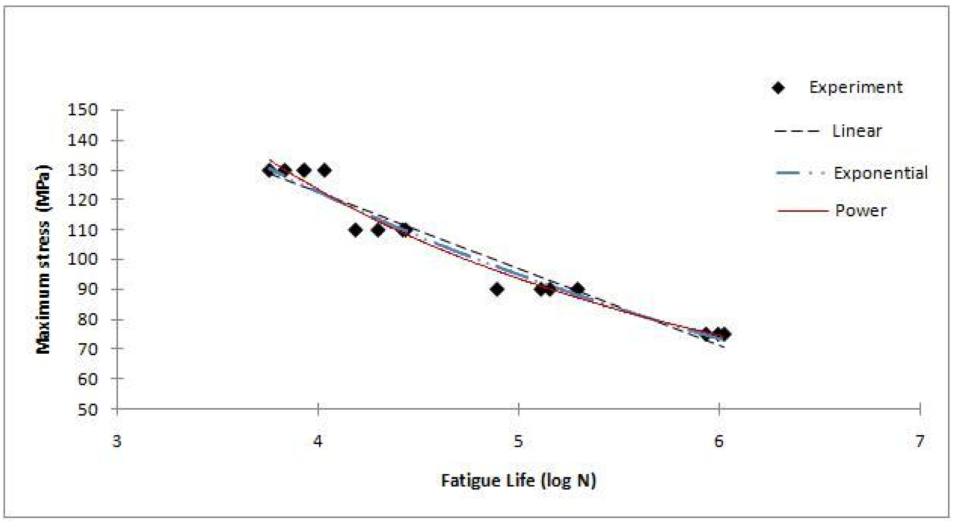

Figure 2-9 Various S-N curve fits on semi-log plot to fatigue data taken from [40].

In Figure 2-9, linear fitting is shown by dash line, exponential fitting is shown by solid-dot line and power fitting is shown by solid line. It can be seen that each curve fits well to the fatigue data.

There is no common agreement between researchers which of the two formulas is preferred and more representative for fitting fatigue data in hand. Therefore, different fatigue equations or expressions were selected and used by researchers in the fatigue field. Log-log expression was preferred by Kawai et al. [35, 36] for fitting the off-axis fatigue behaviour of unidirectional carbon/epoxy composites. Power law fitting with four parameters was chosen by Xiao [37] for modeling of load frequency effect on fatigue life of AS4/PEEK $[\pm 45]_{4s}$ laminates. On the other hand, Michel et al. [38] found that fatigue strength of AS4/PEEK $[-45/0/+45/0]_{8s}$ laminated beam in bending followed a lin-log relationship. For a case where the stress-life relationship is highly nonlinear, a modified stress-life expression is needed to cover all fatigue life range, as was done by Xiao [36] using higher power expression. Mandell et al. [39] also noted that woven fabrics and chopped strain composites showed noticeable nonlinear stress-life trend on a semi-log plot.

2.3.2.2 Reliability Aspects of Fatigue Life Evaluation

Commonly, repeated fatigue testing at particular stress level *S* will produce different fatigue life values. Similarly, fatigue testing at different stress levels may yield the same fatigue life. These forms of variation or scatter are well-known as inherent characteristic of fatigue testing as illustrated in Figure 2-10.

As described in the previous section, experimental fatigue data is usually described by Equation (2-2) and (2-3). The procedures will yield me(di)an life that equals to 50% reliability. The fatigue life scatter is then represented by taking single value of life cycle of mean fatigue life, as shown in Figure 2-10. In the current work, the mean fatigue lives are chosen and used in the modeling. Although characterization of fatigue life at other reliability values is not the subject of this study, its description is also given subsequently for clarity. For further discussion, references [41, 42] should be consulted.

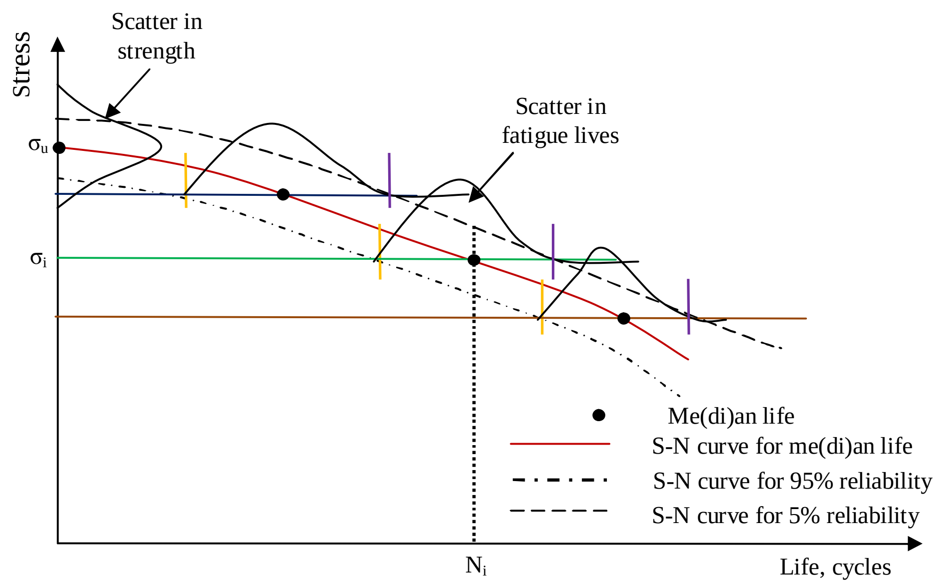

Figure 2-10 Scatterband in fatigue lives and fatigue strength.

It is sometimes necessary to get characterization of fatigue life at other reliability values, for example at 95% reliability, especially for critical applications such as in nuclear power plant. In such a case, the *S–N* curve takes the lower-bound value of fatigue life at a given stress level and gives a conservative estimation of fatigue life. *S-N* curve for 95% reliability is shown by dashed line in Figure 2-10. In contrast, *S-N* curve for 5% reliability is represented by the upper-bound of fatigue life at particular stress level.

It is clear that there are upper and lower bounds to fatigue lives at a particular stress level, each of which corresponds to a particular reliability value. The tolerance bounds are expressed in both reliability and confidence values or in notation RXCY. For instance, R95C95 ensures that there is a 95% possibility of survival (reliability) with a 95% confidence level for a fatigue life at a specified stress level. In other words, the R95C95 ensures that majority of the fatigue data will fall above the minimum value of fatigue life.

The scatter in fatigue life evluation represents the inherent variability in material quality from coupon to coupon. Generally, fatigue lives for polymer matrix composites spread over approximately one to two decades [1]. Various sources of the scatter are summarized in Table 2-2.

Table 2-2 Various aspects and sources of fatigue life scatter

Aspects of scatter	Possible sources of scatter
Material	Variations in fibre and matrix properties
Production/Fabrication	Geometry and size, surface quality, pre-treatment, manufacturing conditions
Load	Applied stress/strain level, *R* value
Laboratory/Testing	Plate-to-plate, lab-to-lab, machine-to-machine variation, accuracy of test equipment, personal/technician skill
Environment	Temperature, humidity, aggressive/corrosive environment

2.3.3 Constant Life Diagrams (CLD)

From previous discussion, it is clear that *S-N* curve is very useful for modeling fatigue behaviour of a material, whether in terms of stress-life, strain-life or strain energy-life. It also can be extended to include any environmental effects such as high temperature, corrosive environment and moisture.

Nevertheless, *S-N* curve has limitation in modeling fatigue data as its range of applicability is limited to specific fatigue stress state or stress ratio-*R*. For example, with the same lay-up, *S-N* curve of a composite material at particular *R* value can not be applied to other *R* values, because mean and amplitude stresses have changed. Many *S-N* curves must then be established to get a complete information of fatigue behaviour of the material.

Of course, it is not always possible to simulate every variation of stress condition in fatigue testing, because it is very costly and time consuming. Even if only thebstress ratio value is varied, an infinite number of testings must be performed. This renders the practical application of *S-N* curve to one particular stress ratio *R* value. On the other hand, a major challenge in composite design is to predict the life of a composite structure subjected to complex loading [43] where the amplitude and mean stress vary along its service life.

In recent years, many researchers have proposed and developed procedures to extend the *S-N* curve so that the range of applicability of the modeling could cover various fatigue stress states or stress ratios [44-46].

Generally, the procedures incorporated a “master curve” or “master diagram”, where the same fatigue lives are connected by one line over a spesific variable of interest. The idea of a fatigue life modeling is to cover general loading conditions for example varying mean and amplitude stresses, but at the same time keeping the number of *S-N* curves (testing) needed a minimum. Such a diagram is called constant life diagrams (CLD) [44, 45].

In relation to *S-N* curve, CLD is another way to represent *S-N* curves and it is very useful in fatigue life assessment under variable amplitude loading. Figure 2-11 shows the transformation or projection of several *S-N* curves into a CLD. Viewed in 2D, CLD has coordinates of stress amplitude (σ_a) and mean stress (σ_m). Recall Figure 2-1 for a schematic representation of CLD in normalized mean stress-normalized amplitude stress plane.

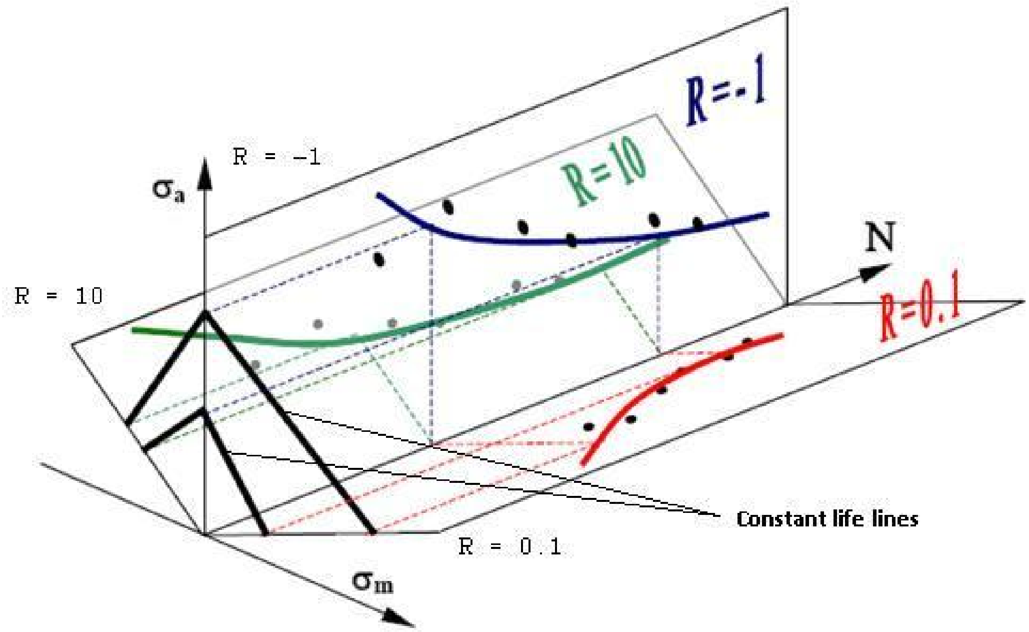

Figure 2-11 Projection of *S-N* curves to form a CLD.

In the CLD, the constant life lines connect points with the same estimated lifetime, as a function of the mean stress and the amplitude stress. It is also clear that the points along each radial line are the points of *S-N* curve for a specific stress ratio-*R*. The relationship between the stress amplitude (σ_a) and the mean stress (σ_m) for each of the radial lines is described in Equation (2-4):

$$\sigma_a = \left(\frac{1-R}{1+R}\right)\sigma_m \tag{2-4}$$

except for R = -1 where $\sigma_m = 0$ and $\sigma_a = \sigma_{max}$.

Performing many fatigue experiments at several stress ratios will produce more representative and accurate CLD. In practice, using fatigue data from three stress ratio-*R* values is enough for building CLD, where each of the three stress ratios is taken from different fatigue loading sectors Tension-Tension (T-T), Tension-Compression (T-C) and Compression-Compression (C-C). For example R = 0.1, -1 and 10, and R = 0.2, -1 and 5.

Looking at the CLD, three regions or sectors of T-T, T-C and C-C of fatigue are represented clearly. Using the diagram, different conditions of fatigue with variable mean and amplitude stresses having the same lifetime could be identified and used easily. Therefore, the operational range of varying mean and amplitude stresses with the same fatigue life estimation could be assessed to meet with the requirements of structural design under complex loading. In this way, fatigue lives under variable amplitude loading conditions can be assessed in an efficient manner.

To summarize, the contents of this chapter are highlighted again as follows: recent works in the field application of NN for predicting fatigue life of composite materials is presented, showing very active research in the last decade concerning NN as a new route in fatigue life assessment of composite materials. Brief discussion of composite materials is also presented. Some important aspects of fatigue of composite materials then followed. Finally, treatment on fatigue life assessment of composite materials under variable loading conditions, which is the central theme of the current study, is introduced and described by the use of constant life diagrams (CLD).