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State of the Art in Fatigue Modelling of Composite Wind Turbine Blades

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Abstract

This paper provides a literature review of the most notable models relevant to the evaluation of the fatigue response of composite wind turbine blades. As wind turbines spread worldwide, ongoing research to maximize their lifetime - and particularly that of wind turbine blades - has increasingly popularized the use of composite materials, which boast attractive mechanical properties. The review first presents the wind turbine blade environment, before distributing fatigue models broadly between three categories: life-based failure criterion models, which are based on S-N curve formulations and constant-life diagrams to introduce failure criteria; residual property calculation models, which evaluate the gradual degradation of material properties; and progressive damage models, which model fatigue via the cycle-by-cycle growth of one or more damage parameters. These are then linked to current testing standards, databases, and experimental campaigns. Among the fatigue modeling approaches covered, progressive damage models appear to be the most promising tool, as they both quantify and qualify physical damage growth to a reasonable extent during fatigue. The lack of consensus and shortcomings of literature are also discussed, with abundant referencing.

Keywords:
fatigue, constant amplitude fatigue models, non-linear fatigue models, failure criteria, micromechanical and mesomechanical fatigue modelling.

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1. Introduction

1.1. Background

The first wind turbine to generate electricity was a battery charging machine installed in July 1887 by Scottish academic James Blyth. Megawatt-scale power was subsequently first extracted from the Morgan-Smith wind turbine at Grandpa's Knob in Vermont, USA, in 1941. The turbine was equipped with sizable steel blades, of which one failed after a mere few hundred hours of intermittent operation.

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Today, with the growing necessity to opt out of fossil fuel dependency in favour of renewable energies, wind turbines technologies are the focus of significant research and development efforts. During recent years, wind turbines have experienced a marked increase in their dimensions. Blades are further subjected to increased cyclic bending and torsion loads, which form one root cause of fatigue in wind turbine blades. In general, wind turbines should have an operational life of at least 20 years however, given the considerable investments required to install and operate large wind farms, accurate lifetime prediction methods for the turbine are required to ensure the durability of these turbines.

The attractive mechanical properties of composite materials justify their growing use in wind turbine applications, but also a plethora of other areas: automotive, aerospace, and more. The word *fatigue* is defined by the ASM [1] as the phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the ultimate static strength of the material. One of the first papers on fatigue was published by A. Wöhler, a nineteenth century technologist in the German railroad system. Ever since, fatigue has been the subject of substantial research; yet we still cannot fully characterize it, especially mechanically or environmentally.

1.2. Objectives

Research undertaken so far in this field has mainly focused on static and dynamic fatigue loading of composite wind turbine blades. Among the great many models for fatigue response prediction that have been added to the literature, there are ostensible overlaps, voids, and ambiguities that must be addressed in order to identify the best course of action for research in this field. Experimental characterization of fatigue behaviour of composite materials is time consuming and expensive. Generalization by extending and extrapolating of experimental results for composite laminates is not straightforward and sometimes impossible. That is why modelling fatigue life is an important axis of research and one that deserves reviewing today, given the plethora of failure criteria and models developed, some describing specific load cases and others offering a more general scope of application.

By considering the complexity of the fatigue failure of composite materials, the level of present knowledge and shortcomings of existing models, the necessity of development of more general models with fewer limitations can be induced [2], and especially the opportunities for research can be revealed. The main objective of this literature review is thus to compare and contrast some of the most important models and approaches developed in the last three decades to attempt in modelling the fatigue response of composite laminates.

This review aims to provide an overview of the current methods, in comparison to the other ones and most prominent theories, through a critical viewpoint, so as to be constructive and conclusive. Despite the fact that the fatigue behaviour of metals are already well-developed and validated, their ”conventional” fatigue models may not be applied to composites due to their high anisotropic and heterogeneous behaviour. The underlying aim is to identify new paths for future improvements and shed light on the most ambiguous aspects of composite fatigue research, particularly in the evolving case of wind turbine applications.

2. Problem Definition

2.1. Loading of Wind Turbine Blades

Fatigue can have a direct or indirect effect on the overall performance of wind turbine blades, accelerating their degradation process and decreasing their energy production efficiency. According to Brondsted [3], fatigue relies on three design drivers of the blades; aerodynamic performance (blade shape), power performance (power efficiency, power curves, noise) and loading performance. Wind turbine blades and rotors are subjected to a high number of loading-unloading cycles, with highly stochastic loads (at times reaching extremes) during their baseline service life of 20 years. Mandell [4], and van Delft [5], have estimated that number to be around 10^8 to 10^9 in a given life. Blade loads include deterministic, easily predictable components as well as non-deterministic components evaluated in a statistical or probabilistic fashion with physical considerations [6]. Wind turbine blade loads act in two orthogonal directions [2], *flapwise* and *edgewise* service load as seen in Figure 1.

- *Flapwise load*: carried by main spar, due to wind action (aeroydnamic loads) and acting perpendicularly on the rotor plane; loads present high variability in both amplitude and mean, thereby inducing high scatter in load history data.

- *Edgewise load*: carried by blade reinforcement, consisting of gravitational loads arising from the blade's weight, and torsional loads driving the turbine. This loading is more deterministic and changes direction twice during each revolution. The frequency distribution contains two peaks [6], corresponding respectively to the wind-loading-induced centripetal load and blade self-weight gravitational load.

The above loading environment results from the distinctive structural characteristics of wind turbine blades compared to other common composite structures (such as those found in aerospace and automotive applications). The thickness of a wind turbine blade is the result of a trade-off between the ideal slenderness for aerodynamic efficiency and ideal thickness for structural integrity. As loading and stresses increase toward the rotor hub, wind turbine blades tend to increase in thickness toward the center of rotation (i.e. at the blade root), and gain in slenderness toward the tips. Wind turbine blades can be considered slender bodies and as such, their slenderness favours a uniaxial stress profile on the blade cross section. It must be also be noted that both flapwise and edgewise loadings produce shear and torsional loads that contribute to the effects of blade fatigue over time. While this shear component is not always thoroughly accounted for in some of the more simplified fatigue models we shall explore, new algorithms and approaches more accurately account for such effects, as we shall see.

As wind turbines increase in size, the edgewise fatigue loading becomes increasingly relevant for life prediction, as shown by Kensche [7]. In addition, the torsional eigenfrequency drops, with a risk that it may couple with lower bending modes, with disastrous consequences. Toward the trailing and leading edge of the blade structure, gravity increasingly dominates the stress and strains applied to the load-bearing structure in the rotor plane. An alternating, cyclic stress emerges as a result, with mean stress almost null. Furthermore, rapid change in wind direction known as gusting can be hazardous especially if the natural frequency of the wind gusting coincides with the turbine structure [8]. Wind shear, also referred to as wind gradient and described as the variation of wind velocity with height (or horizontal distance), can exacerbate the effects of gusting.

Small scale wind turbines are also widely present on the market for diverse applications. They share common features with the large scale ones in terms of structural design. Nevertheless, as their surface exposure is decreased, they are less exposed to environmental hazards and load variation generated by wind-loading-induced shear surface and gravity [3]. Furthermore, rotational speed (centrifugal stresses) and gyroscopic loads are higher in comparison to large wind turbine blades, implying higher fatigue cycles.

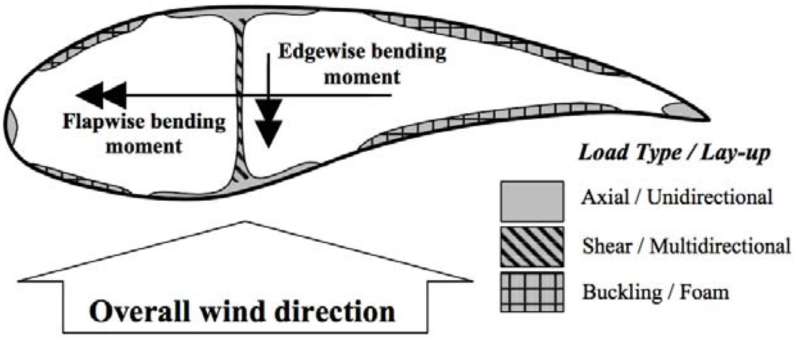


Figure 1: Wind turbine blade cross-section and load plane definition [2].

The impact of load variability and turbulence on fatigue life should be highlighted. Riziotis *et al* [9] performed numerical modelling of wind and wind turbines of the 0.5MW class and identified turbulence intensity to bear the most significant impact on fatigue load contributions, and therefore fatigue life of the turbine blade. Further, according to Mouzakis [10], terrain complexity surrounding the wind turbine could account for about 30% of additional fatigue loading contribution, including cyclic bending loads. According to Lange [11], the way loading history data is modelled strongly affects fatigue modelling reliability. A great number of complex, non-linear and irregular environmental factors specific to a given wind turbine's location therefore seemingly come in play when it comes to decomposing fatigue loading contributions on the particular wind turbine blades. An effect that can be advantageous to reduce the mean blade loading is called coning. It is the bending of the rotor blades in high winds that introduces centrifugal force loads which acts against the aerodynamic steady thrust loads however the coning effect can cause oscillations. Transient loads at start-up and shut-down of the turbine may lead to fatigue damage.

2.2. Material Selection

2.2.1. Choice of Fibres

Composite stiffness is largely dependent on the stiffness of its fibers and their volume fraction. So far, the most commonly used fibres have been the affordable glass fibres, although there is a clear growing tendency towards incorporating carbon fibres.

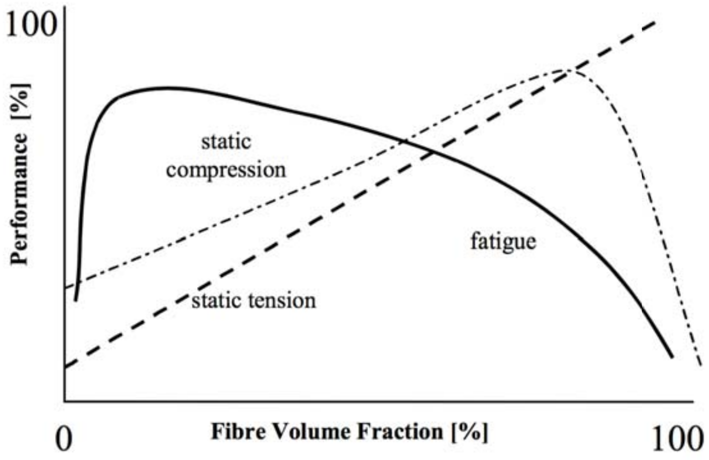


Figure 2: Influence of fibre volume-fraction on composite performance (not to scale) [2].

Most often, E-glass (i.e. borosilicate glass) fibres are used as the main reinforcements in composites. Their main properties are summarized in Table 1. As the volume fraction of fibres increases in unidirectional composites, the stiffness, tensile, and compression strength increase proportionally. Nonetheless, at high fibre volume fraction (above 65% [12]), there may be resin-deprived areas, thereby reducing fatigue performance. Figure 2 schematizes the relationship between fibre volume fraction and overall composite fatigue performance. A common glass fibre volume fraction in glass/epoxy composites is 75% [12].

S-glass (i.e. high-strength glass) fibres (Ashwill [13]) and the expensive carbon fibres (limitations in [14]) are a particularly promising alternative to glass fibres. Their properties are compared with those of glass fibres in Table 1 as well as their normalized price with the E-glass material being the reference. Those prices are taken from commercial websites as of January 2018. It has been shown that high strength glasses ultimately provide the best combination of stiffness, strength, and impact resistance [12] as carbon-fibre-reinforced composites are particularly sensitive to fibre misalignment and waviness.

Among other options are aramid (aromatic polyamide) and basalt fibres. The former have high mechanical strength, toughness and damage tolerance. However, they are limited by their weak compressive strength properties relative to carbon [12]. Basalt fibres possess satisfying mechanical properties and represent a tangible alternative to glass fibres: they are 30% stronger and up to 20% stiffer than the former, while remaining cheaper than the carbon option [14]. Hybrid glass-carbon-fibres have emerged as an increasingly attractive option.

Fibre	E (GPa)	ρ ($kg.m^{-3}$)	$\epsilon_{failure}$ (%)	Normalized price
E-glass	70 - 77	2.55 - 2.64	4.5 - 4.9	1
S-glass	86 - 90	2.46 - 2.49	5.4 - 5.8	6 - 10
Carbon	220 - 240	1.7-1.8	0.7	11 - 14
Aramid	133 - 135	1.44	2.5 - 4	13 - 16

Table 1: Properties of prominent fibre materials used in more than 90% of composite wind turbine blades. Normalized prices are valid as of January 2018.

2.2.2. Choice of Matrix

Aligning the fibres as well as being compressive resistant, thermosets (e.g. polyester) are most widely used in the wind turbine industry and represent around 70% of the market for reinforced polymers [2]. With lower viscosity, better impregnation and adhesion between fibres and matrix can be done. However, with the development of ever larger wind turbines, epoxy matrices have become the primary material in wind turbine blade production. While the density of epoxy is very close to that of polyester [12], it provides better fatigue performance and is more durable in comparison. In addition, it is free of toxic styrene, which is present in polyester and produces harmful vapours during the polyester production process. Recyclable thermoplastics are a considerable alternative to thermoset matrices. But their high viscosity nonetheless makes manufacturing large parts from thermoplastic resins a considerable challenge, on top of the high processing temperatures required. A comparative table of the main matrix material used in the wind turbine industry can be found in the Table 2 below. The prices are normalized based on the Polyester cost in January 2018.

One important area of research has been to further developed materials which cure faster and at lower temperatures [12] in order to reduce the processing time and pursue the automation of manufacturing processes. Composite properties were enhanced following the addition of nano-reinforcements such as carbon nanotubes or nanoclays in the polymer matrix. According to Bian [15], graphite particles fibre coatings on glass fibres could increase fatigue life by two orders of magnitude. As put forward by Gamsted [16], fatigue degradation has a strong dependency upon the damage mechanisms at smaller scales. Fabric architecture, fiber content and ply stacking sequence, as well as geometry, produce major differences in fatigue performance; hence more combinations of the above factors should be tested in order to evaluate their impacts on the mitigation of fatigue damage.

Matrix	E (GPa)	ρ ($kg.m^{-3}$)	$\epsilon_{failure}$ (%)	Normalized price
Polyester	3.0 - 8.5	1.38	20 - 50	1
Epoxy	86 - 90	2.46 - 2.49	5.4 - 5.8	3
Nanotubes	220 - 240	1.7-1.8	0.7	60 - 90

Table 2: Properties of prominent matrices materials used in composite wind turbine blades. Normalized prices are valid as of January 2018.

3. Basic Fatigue Considerations

3.1. Composites vs. Metals

Though some of the fatigue modelling theories and methodologies outlined in the sections below originate from metal-based theories, it must be noted that, at the nanometer length scale, composite materials are inhomogeneous and anisotropic, and their behaviour is therefore much more complex than that of metals, which are generally homogeneous and isotropic materials. This complexity is mainly associated with the fact that a variety of damage phenomena – each with their specific growth rates and laws of interaction – can occur in the case of composites, namely (but not exhaustively); fibre fracture, fibre buckling, matrix cracking, matrix crazing, fibre-matrix interface failure, delamination.

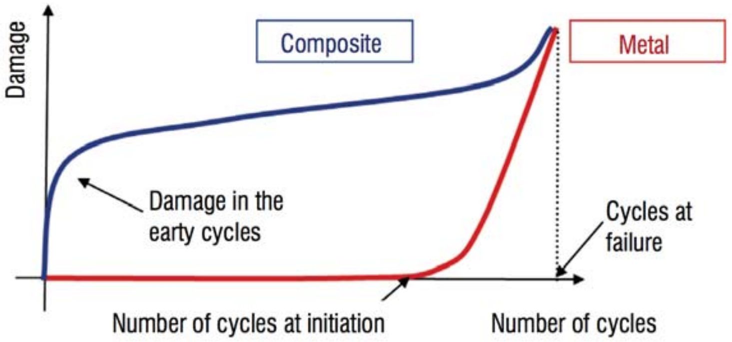


Figure 3: Evolution of damage with the number of cycles, for composites and metals [17].

As described in [18], the difference in fatigue behaviour between fibre-reinforced composites and metals (see [19]) lies in several points. Figure 3 graphically schematizes the difference in damage evolution response between composites and metals.

In the case of metals, gradual and invisible material deterioration occurs almost over the entire material lifetime and thus no – or little – degradation of material properties is observed during the course of fatigue progress [18]. Namely, stiffness remains quasi-constant over the lifetime of the material. Toward the end of the material's life, macroscopically observable small cracks develop across the material and, before long, coalesce in the run up to final fracture. With constant stiffness, the linear relation between stress and strain remains constant all throughout the fatigue process. As a result, linear elastic analysis and linear fracture mechanics are largely applicable to the case of metals.

This is not the case for fibre-reinforced composites, where damage starts very early and the extent of damage zones grows steadily [18], while the type of damage in these zones can change: small matrix cracks can lead to comparatively larger delaminations, for example. Gradual deterioration, in stiffness and strength, leads to a continuous redistribution of stress and a relative reduction of the amplitude of stress concentrations within the component studied under displacement controlled situations.

Therefore, modelling the fatigue process in a fibre-reinforced composite requires the simulation of the complete sequence of damage states and growth of damage inside the component. Consequently, methodologies derived for metals are mostly unsuitable for composites.

3.2. Ply Architecture

The variety of configurations – fibre type, resin and lay-up – that can result in different endurances across composites, poses a heavy contrast to their notably high fatigue performances [17]. Figure 4 shows a comparison of various architectures with regards to fatigue performance. Based on this figure, it is clear that woven composites will be omitted in this review because of its low strength at 10^7 loading cycles.

A difficulty with composite materials is that increasing fibre resistance or matrix toughness, or even improving fiber/matrix bonding, does not always result in an improved fatigue performance, i.e., longer fatigue life and higher fatigue ratio, as discussed by Kaminsky [17].

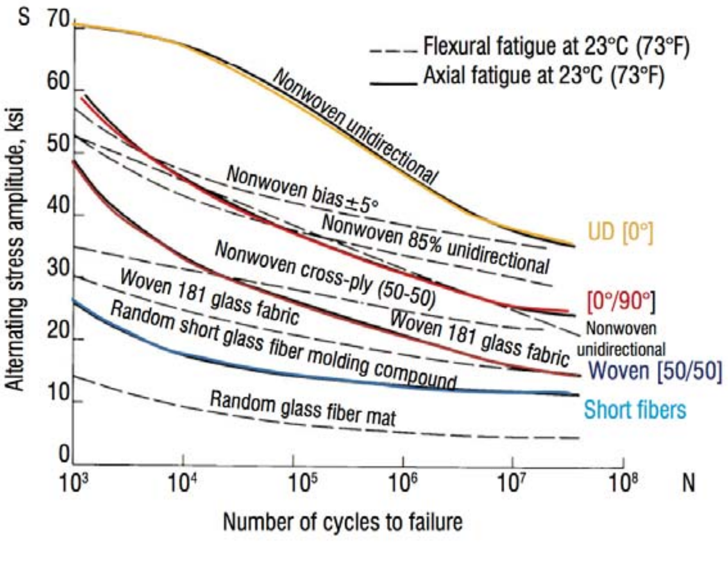


Figure 4: Comparative fatigue strengths of a same resin/glass composite with various fibre architectures [20].

3.3. Structural Details

Ply Drops: As discussed by Sutherland [21], one common feature of blade structures is the use of ply drops in order to customize composite structure thickness. This is done to meet the load-bearing requirements while minimizing weight. The ply drop may be internal, such as to be covered by at least a layer of fabric, or external. Sutherland explains that the internal ply drop creates local stress concentrations initiating failures and thereby restraining fatigue live (see Table III of [21]). Internal ply drops are more resilient to delamination than external ones, as detailed by Cairns *et al*[22].

Locally Higher Fibre Content: As discussed by Sutherland [21], fibreglass laminates are prone to significant degradation in their fatigue properties should the fibres be positioned too close to each other. Indeed, fatigue depends on fibre density, and the density of fibres also translates into local manufacturing defects such as indentations and excess fibre layers. Sutherland [21] shows that a surface indentation produces a knock-down factor F, defined as the ratio of maximum cyclic strain of a uniform coupon to that of a structured coupon at 10^6 cycles [23].

Transverse Cracks: From Sutherland [21], in common layups of composite structures, a high percentage of the fibres are aligned with the primary load directions. Additional off-axis layers are added to prevent splitting and to enhance shear properties. These off-axis layers are often more susceptible to fatigue damage and lead to transverse cracks.

4. Different Models for Fatigue

4.1. Constant Amplitude

4.1.1. S-N Curves

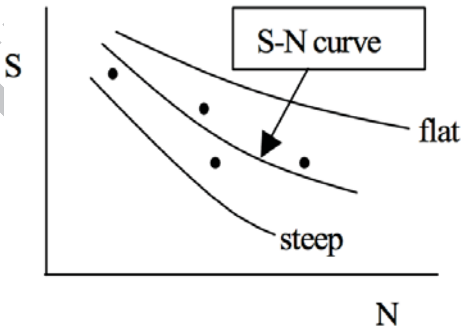


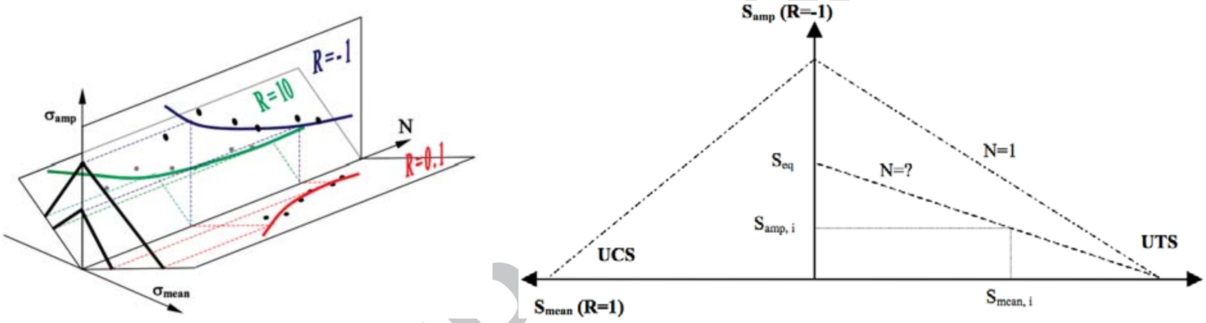
Figure 5: Typical S-N Curve Trends for Composites [24].

Results from fatigue experiments carried out at constant stress ratio $R = S_{min}/S_{max}$ are generally plotted in the form of what is called an S-N curve, which plots the applied stress S against the number of load cycles to failure, N. A sample S-N curve is presented in Figure 5. According to Nijssen [2], several formulations exist for deriving and using the data from S-N curves. Classically, the logarithm of constant amplitude fatigue life N is assumed to be linearly dependent on the governing stress/strains S, or its logarithm [2]; $logN = a + b.logS$. The resulting two formulations of the S-N curve are known, respectively, as a log-log curve – Basquin relation (1910) – and a lin-log representation — Wohler curve (1870).

The use of S-N curves has had a significant influence on blade design. Van Delft *et al.* [5] found a 30% difference in design mass when extrapolating data to low strain states using a log-log representation of the design S-N curve, rather than a lin-log one, with all other variables kept constant. Note, however, that S-N curve formulation often depends on other aspects of the method of prediction; a 1% variation in the parameters a and b give fatigue lives 10- 20% different from the baseline predictions.

4.1.2. Constant Life Diagram

The Constant Life Diagram, or CLD, is essentially a representation of S-N data. Quoting from Park *et al* [25], "CLDs have been created to consider the effect of the mean stress and material anisotropy on the fatigue life of composite materials". The CLD is the projection of the constant amplitude fatigue data on a plane perpendicular to the life axis (i.e. the N-axis). Constant lifelines in the CLD connect points with the same estimated lifetime, as a function of the mean stress and stress amplitude [2]. The different S-N planes all intersect with a straight line, which represents null stress and is also the life axis (see Figure 6a).



(a) Schematic relation between S-N curves and CLD

(b) Linear Goodman Diagram

Figure 6: S-N curves and Goodman Diagram [2]

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The CLD is a very important tool for fatigue life prediction in that it summarizes all information on the material's fatigue behaviour. CLD is not commonly symmetric in the case of composites, unlike for metals. Fibres dominate composite tensile properties (if fibres are predominant) and the matrix provides support to the matrix when subjected to compressive forces. The most commonly used CLD is the classical Linear Goodman diagram (see Figure 6b). Resulting from the Germanischer Lloyd [26] requirements, the Linear Goodman diagram has given way to the Shifted Goodman diagram, in which the summit has moved to the right, compared to the classical Linear Goodman diagram. The reason for the shifted version is to reflect the asymmetry in the CLD evidenced from experiments, while maintaining the simplicity of the Goodman-type diagram [2]. Philippidis [27] presents an ample discussion on Goodman diagram data applications.

4.1.3. Limitations

Widely used in engineering, S-N curves and CLD are limited models to estimate life-time in terms of fatigue behaviour of composites [2].

S-N curves for composites include no fatigue limit, or at least none yet, meaning that the material is considered damage proof at every loading cycle, which is not the case in reality. Thus, every load cycle should be considered damaging. Yet due to the high initial strength and low S-N slope of ordinary composites, detecting a fatigue limit at low loads may take a long time. Scientists have assumed that at a structural level, the fatigue life concept is irrelevant as it only impacts the material locally. Therefore it appears logical to neglect this concept, even though Ryder and Walker [28] tested two laminates in tension-tension, and tension-compression fatigue acknowledging the presence of a fatigue life endurance limit. However,they could not prove it. Furthermore, rather than stress, strain should be used in the data process of S-N curve formulas as strains are equal for all laminae in a composite. Another issue related to the S-N model is its sensitivity to the reference line and data fitting method employed, which impacts the values of the constants used in S-N curve formulation equations. Finally, a plane stress assumption is made; however, its applicability is restricted to thin, unnotched laminates [29].

With regards to CLDs, it must be noted that they incorporate a singularity in the R-value [2] when the load nature changes from compressive to tensile. Furthermore, CLDs also include regions pertaining to creep and static failure, which are not clearly distinguishable from regions of pure fatigue. Moreover, constant life is associated to an average fatigue life prediction. This generalization flaws data precision, as data scatter is not represented.

4.2. Variable Amplitude

4.2.1. Damage Rule Formulation

Miner's Rule

The *Palmgren-Miner linear damage rule* (1945), is one of the most widely recognized linear cumulative damage models for fatigue failure analysis, and likely among the simplest. It states that, for k different stress levels to which the material is subjected, and given the number of cycles to failure at the i^{th} stress state, σ_i, to be N_i, then the damage fraction D is related to the number of load cycles by the Equation 1 where n_i is the number of load cycles at stress state σ_i and D, the damage fraction, is the fraction of life consumed by exposure to the cycles at the different stress levels. By this model, failure is predicted to occur when the damage fraction equals unity. Post et *al.* [30] have stated — after extensively reviewing damage accumulation models and comparing their predictions with experimental data — that Miner's rule represents the most conservative of damage model, for both small and large wind turbines. A subsequent, non-linear, version of Miner's Rule (Equation 2) was developed by Owen and Howe [31], which states where A and B are data-fitting constant parameters.

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = 1 \qquad (1)$$

$$D = \sum_{i} \left[A\frac{n_i}{N_i} + B\left(\frac{n_i}{N_i}\right)^{C} \right] \qquad (2)$$

Crack Propagation Models

Linear crack propagation models, such as those covered by Lampman [32] and Hertzberg [33], have been successfully applied in the fatigue analysis of wind turbine components [34]. These models postulate that pre-existing cracks of length a_0 subjected to N load cycles will grow at a rate da/dN (which depends on material properties) to a final length a_f. Crack growth behaviour is often determined as a function of the stress intensity factor, K, which itself is a function of specimen geometry (see Sutherland [34]). Non-linear crack propagation models are included in the broader category of property degradation models, which are covered in later sections.

Limitations

A shortcoming of Miner's rule is that it fails to predict sequence effects, which are the observation that depending on the sequence of loading applied to a component, the damage mechanisms undergone by the component vary. This is substantially explored by Wahl [35], who also highlighted the model's failure to consider *sudden death* response, corresponding to failure due to significantly high stress. In the case of wind turbines, the strong variation in material properties and loading configurations induces marked uncertainties. According to Sutherland [34], "differences of a factor of 2 between damage predictions and measured lifetimes are not only common in wind turbine applications, they should be expected".

5. Life-Based Failure Criterion Models

5.1. Linear Degradation Models

Experimental and analytical work led to life-based failure criterion models that are mostly empirical or semi-empirical. Considering once again the S-N curve, Fawaz and Ellyin [29] have suggested a semi-logarithmic linear relationship between the cyclic applied stress S and the total number of cycles to failure, N, as $S = mlog(N) + b$ where m and b are material parameters. This multiaxial failure model has showed rather satisfactory levels of accuracy and correlation with experimental data gathered for a number of material configurations and load cases. The model is rather general as it accounts for a variety of parameters — multiaxiality, fibre orientation and R-value — giving more degrees of freedom in the loading and material configuration. In addition, the model was developed based on the assumption of plane stress, which is valid only for thin unnotched laminates. Should free edge effects be taken into account, be they linear or circular, a third dimension of stresses (out of plane) would be introduced in the stress state.

Philippidis and Vassilopoulos [36] compared their experimental results with those of Fawaz and Ellyin [29] and outlined the lack of accuracy of the criterion's predictions for tension-torsion fatigue. However, as suggested, this fatigue strength criterion requires a new set of experiments for each fibre architecture or laminate stacking sequence. A thorough comparison is provided by Degrieck *et al* [18].

Another interesting model has been proposed by Miyano *et al* [37, 38], who have worked on the tensile fatigue response of carbon-fibre-reinforced (CFRP) composite materials under arbitrary frequency, stress ratio, and temperature. The model aims to provide a simpler methodology for estimating the life of polymer composites than traditional S-N curve approaches and may be extended to polymer-composite structures under combined loading and temperature histories. The procedure is to first obtain empirically a "master curve" for constant-strain-rate and fatigue strength at zero stress ratio, and finally the fatigue strength is related to frequency stress ratio, time to fatigue failure, and temperature by a linear relationship. A major takeaway of this model has, of course, been the strong dependence of creep and especially fatigue strength on temperature, loading rate, and number of cycles to failure. The stated model hypotheses were shown to be valid for the case of CFRP of PAN based carbon fiber/epoxy composite laminates.

Andersons and Korsgaard [39], noticed that creep accelerated under cyclic loading in the case of glass / polyester composites used as wind turbine blade material. Introducing a fatigue damage parameter, D, they quantified life fraction as a measure of this parameter. They studied the impact of fatigue damage over the course of the material's life on its viscoelastic response, and the two were related via a damage-dependent effective stress. The test data observations outlined the convergence of fatigue strength toward creep strength with increasing mean stress, which is unlike what is seen in a Goodman diagram, where the convergence is toward the ultimate tensile strength (UTS).

More recently, a simplified, iterative, load-spectrum-based method has been developed, which is also known as Damage Equivalent Load (DEL) [40]. Using Miner's linear damage rule, this method does not require any specific knowledge of the blade structure or geometry. To reduce potential errors induced by the strength analysis of conventional test-load methods, loads are not converted into stresses S but instead into applied moments M. Confined to a specific load-range, a family of fatigue curves is plotted following the relationship of $M_a = M_u \times n^{(-1/m)}$, with M_a the amplitude moment, M_u ultimate moment of the blade and m the slope of the curve. Extrapolation using a symmetric Goodman diagram leads leads to the equivalence damage ratio. Kazacoks [41] applied this method to calculate fatigue loads and examine their trends with respect to wind turbine scales in the form of power law curves. Perez [42] focused on the input selection — such as central moments and signal span — and model configuration, to reach the lowest error possible. Estimated at below 4%, this error level demonstrates the potential of such models to accurately predict loading states and hence the fatigue life of wind turbines.

A plethora of linear models are available in the literature, and many references have been provided by Nijssen [2], Sutherland [6, 21, 34], Degrieck [18], Plumtree and Cheng [43] to mention but a few.

5.2. Non-Linear Degradation Models

5.2.1. Polynomial Criteria

Hashin and Rotem [44] developed a quadratic failure function which distinguishes two failure modes, namely of fibre and matrix, each with their respective terms in the quadratic polynomial criterion. The criterion is expressed in terms of three S-N curves, with the ultimate strengths depending on the level of fatigue stress. As it has been the case with other criteria, these S-N curves are determined empirically, and are the results of data from uniaxially loaded stress-tested specimens. Due to the assumption of a plane stress state in a laminate, this criterion bears inherent shortcomings when cases more complex than that of a unidirectional-plied laminate are considered. A subsequent micromechanical model, developed by Reifsnider and Gao [45] and based on the Mori-Tanaka method [46], takes into account material inhomogeneities and the interfacial bond. The key difference with the Hashin and Rotem criterion is that mean stress terms or average stresses are taken. Yet, one must take into account the prospect of a non-perfect bonding between fibres and matrix. This method indeed factors imperfect fibre-matrix interfaces into the model by modelling the interface as a "thin layer with spring-like behaviour", as outlined by Degrieck [18]. With the introduction of fatigue failure functions, under tensile loading for fibre χ^m and pure matrix χ^f, and reinforcement-free matrix subjected to shear stresses S^m, Reifsnider-Gao [45] failure functions can be obtained.

Lawrence Wu [47] introduced a macroscopic-scale failure criterion, which is in fact based on the Tsai-Hill fatigue failure criterion. The criterion is a second-order polynomial composed of functions of the lamina peak stresses in all three directions (three-dimensional stress state). The stress-states were obtained from Finite Element Analysis, in which free-edge effects were accounted for. In addition, inclusion of thermal factors seemed to improve the results.

The Tsai-Hill criterion for plane stress multiaxial fatigue was subsequently modified by Jen and Lee [48] to produce a more general fatigue failure criterion. In this new criterion, fatigue strength is dependent on number of cycles to failure, loading frequency, and stress ratios, which are all determined in advance experimentally. In the paper, the theory is tested against experimental data from carbon-fibre reinforced PEEK composite laminates, but the case of angle-plies, namely $[\pm 45°]_{4s}$, presented significant errors, meaning the method is prone to future progress.

Amongst multiaxial fatigue modelling research effort, Philippidis and Vassilopoulos [36], unearthed a multiaxial fatigue failure criterion much like Tsai-Wu quadratic failure criterion [49]. The values of the static failure stresses have been replaced by the material's S-N curve values in the equivalent directions and loading conditions. Between three to five S-N curves are required to be determined experimentally. It is worth noting that, in this model, laminate properties (and not ply properties) were used so as to enhance the applicability of the criterion to a variety of fibre architectures and stacking sequences. In the case of multiaxial loading, the model produces satisfactory results. However, for each laminate sequence a new series of experiments is required, as noted earlier, which is highly inefficient.

5.2.2. Power-Law-Based Criteria

With regards to CLD-based models, Harris and Gathercole *et al* [50, 51, 52] have introduced a "Normalized Constant-Life Model" that outputs which particular combinations of mean stress amplitude and peak stress amplitude are equivalent in terms of the resulting number of cycles to failure. The semi-empirical model is composed of linear functions of the logarithm number of cycles to failure in this instance. The resulting constant-life curve is bell-shaped, expected somewhat asymmetric. Harris [53] provides the step-by-step procedure to follow in order to carry out the constant-life analysis and obtain the model output; a group of constant-life curves corresponding to the material and loading. The CLD developed by Harris *et al* is essentially based on a nonlinear fit of S-N curve data, embodying experimental reality more accurately than a linear fit. Yet, as pointed out by Park *et al* [25], this model comprises an intricate multivariate data fitting procedure, as well as a necessary adjustment of parameters based on empirical considerations and fatigue data. The model underlying preparation is thereby complex, time-consuming, and not accurate.

Another directions, often cited model, originated by Ellyin & El Kadi [54], presents the use of strain energy density as a fatigue failure criterion. A power law relationship related the number of cycles to failure to the total energy input. Here again, the assumption of plane stress was deemed valid when determining the strain energy density. This version of the criterion is therefore inapplicable to cases of major through-thickness stress components.

The case of variable amplitude loading — which is a better match with the reality of wind turbine blade fatigue loading — has been studied extensively by Bond [55], especially in the particular case of glass-fibre-reinforced polymers. Bond introduced a new formulation of the S-N curve of glass-fibre-reinforced polymers, representing fourth-order polynomial functions of the ratio range. The ratio range arises from the Goodman diagram and provides sequential modes of cyclic loading. One particularly unclear aspect of this model is how these relations are derived.

Research work has also been carried out by Xiao [56] regarding carbon-fibre-reinforced polymers with thermoplastics. Xiao [56] developed a model relating the fatigue life of these composites to the load frequency via a power-law relation for the formulation of the the S-N curve, with fitting parameters. Degrieck *et al* [18] have discussed Xiao's method in more depth.

5.3. Critical Plane Approach

According to Plumtree [43], *critical plane concept* illustrate the observation that fatigue cracks initiate and propagate along critical planes; planes that experience the highest normal stresses and strains. In light of this concept, Findley [57] claimed that a fatigue parameter should be expressed by addition of the alternating shear strain and some part of the normal strain in the critical plane. Further, Brown an Miller [58] deepened this approach based on mechanisms of fatigue crack growth expressed. This approach has provided good correlation with multi-axial tests on isotropic materials under a broad range of loading conditions and specimen shapes. The multi-axial fatigue parameter also successfully correlated the established fatigue data of composite materials. Nonetheless, some terms in the formulation fail to incorporate mean stress and to fully abide by continuum mechanics laws. This shortcoming was partly overcome by Glinka *et al* [59], who proposed a strain energy criterion based on the former.

The original critical criterion plane concept has been extended from the multiaxial case to the uniaxial/unidirectional case. Generalised fatigue parameters should take into account multi-damage mechanisms and interactions between fibres and matrix [43]. Plumtree and Petermann [43] discuss the approach used to extend this criterion [43] into their *unified fatigue parameter*, which incorporates both normal and shear contributions. As a result, the energy rather than stress or strain components is considered. Further experimental verification is necessary to extend the parameter to loading other than unidirectional tension. Temperature should also be considered as a variable to assess its impact on fatigue life.

6. Phenomenological Residual Properties Models

Two directions of research have developed within this progressive damage evolution modelling approach: phenomenological models and progressive damage models. While the former (discussed in this section) expresses the growth rate of damage as a function of macroscopically observable properties, the latter (discussed in the following section), takes a more micro-mechanical approach and is based on the actual damage mechanisms. The following models, based on the phenomenological analysis of residual material properties, proceed by analyzing residual properties, namely stiffness and strength. These models look at the underlying damage phenomena occurring throughout the material lifetime, and especially their contribution to the gradual degradation of the material properties, until a threshold value is reached. Phenomenological models therefore directly relate static data and fatigue response of composite specimens. The first papers on phenomelogical models were published in the 70s; more came later in the 90s [60]. However, the popularity of these models in research began to decline gradually in favour of progressive damage models (discussed in the next section). The main reason for this shift of interest was due to the experimental cost of the phenomelogical models, requiring coupons to be tested till static failure to obtain exhaustive characterization of each materials arrangement, layup and loading conditions.

6.1. Residual Stiffness Models

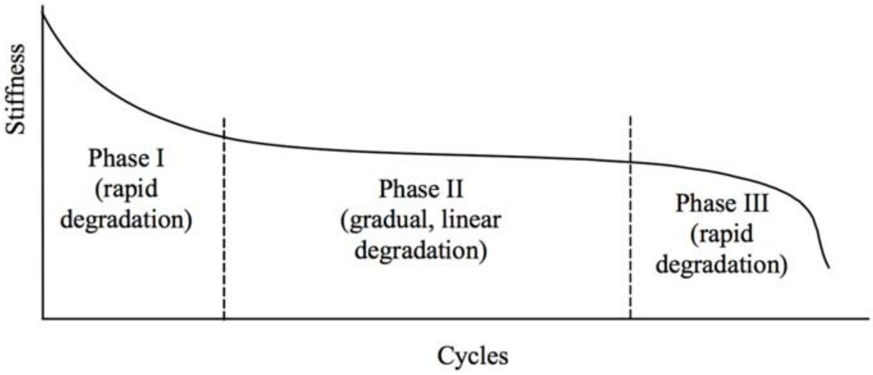

Figure 7: Stages of Observed Stiffness Degradation in Composites [2].

Stiffness is a potentially interesting measure of the laminate's condition and fatigue resilience, since it is quantifiable through non-destructive tests [2]. Figure 7 illustrates the three different stages of observed stiffness degradation in composites.

The description of stiffness degradation often introduces a damage variable D_{ij}, defined as $D_{ij} = 1 - \frac{E}{E_0}$, where E is the elastic modulus in the damaged state and E_0 is the undamaged modulus. One of the first models developed was the result of work by Reifsnider and Talug [61], who developed a baseline "philosophy" of damage development in laminated plates under cyclic loading, based on a so-called "Characteristic Damage State" (CDS) which is a function of laminae properties: stacking sequence, fibre orientation, and fibre architecture. From experimental observation, each laminate has its own characteristic damage state, confirming the idea that, unlike metals, composites have extremely unique damage mechanisms proper to each laminate. The approach is, however, rather basic and does not take into account the effect of holes and notches, as well as the effect of buckling or flexure.

Fatigue Modulus

The concept of Fatigue Modulus was first proposed by Hwang and Han [62, 63], who define it as the slope of applied stress and strain at a given cycle. The fatigue modulus is assumed to degrade following a power law with respect to the number of cycles and the fatigue life is found by integration. Another key assumption was that of a linear relationship between stress and strain, so as to obtain an equivalent of Hooke's law where the elastic modulus is replaced by the fatigue modulus.

The most recent cumulative model the best fit D_{ij} with experimental data. The associated failure criterion is $D_{ij} = 1$, that is, failure occurs when the sum of the damage values at each level of stress equals unity. Subsequent works by Kam *et al* [64, 65] built on these cumulative damage models to study the fatigue reliability of graphite/epoxy composite laminates subjected to variable loading. For a more detailed review of phenomenological-type cumulative damage models, refer to works by Fatemi and Yang [66], which, despite focusing on metals and alloys, present various models extended to the case of fibre-reinforced composite laminates.

In another paper, Hahn and Kim [67, 68] proposed that fatigue failure would occur when the fatigue modulus decreases sufficiently to be within the statistical scatter of modulus distribution in a quasi-static stiffness test. This criterion was dubbed the "secant modulus criterion" and reviewed by O'Brien *et al* [69], who concluded that this concept was valid for all but unidirectional laminates, in which no marked modulus degradation was observed in experiments.

Strain-related Damage

Sidoroff and Subagio [70] use in their model the classic relation of damage and stiffness degradation, and states a relationship between damage growth rate and strain amplitude in tension, and $dD_{ij}/dN = 0$ in compression. This model was built on by Degrieck and van Paepegem [71, 72] to produce a finite element analysis code, which was used for the simulation of the fatigue response of glass/epoxy composite laminae subjected to fatigue loading. Stresses were continually redistributed over the course of fatigue loading, and the model successfully predicted this phenomenon. This is a major step forward in the direction outlined earlier by Reifsnider [61]. Extensions of this model now sometimes work with stress amplitude rather than the original strain amplitude.

Equivalent Cycles Approach

Whitworth [73] developed a residual stiffness model as a function of the normalized applied stress range, defined as $\bar{S} = S/R(0)$, where $R(0)$ is the static strength (i.e. R is a function of the number of load cycles). This model has been particularly interesting when extended to the case of variable amplitude fatigue loading using the *equivalent cycles approach.* The practicality of this approach, particularly in the case of variable amplitude fatigue life modelling, is to transform the number of cycles at a given stress state in a variable amplitude loading group into an equivalent number of cycles at a reference stress state that results in the same level of damage as the original loading configuration.

Multi-loading Stiffness Reduction

Fatigue life predictions are empirically sourced from observations of wind turbine blade materials subjected to constant amplitude loading, variable amplitude block loading, and stochastic spectrum loading according to Brondsted *et al* [74, 75]. The stiffness reduction with number of cycles is modelled as a ratio of E_N/E_1 where $E(N)$ is the static modulus after N cycles and E_1 the initial cyclic modulus. Empirically approximated as $E(N)/E_1 = A \times N + B$, where B is a constant and A is supposed to represent a power law relationship. This model assumes a history-independent stiffness degradation model, and can be used for fatigue life prediction of composites under variable amplitude loading conditions.

Further reading for the case of stiffness reduction in fibre-dominated composites has been provided by Yang *et al* [76]. Subsequent works by Lee *et al* [77] extended the model to laminates subjected to variable amplitude loading. In another paper, Hansen [78] also introduced a fatigue damage development model for impact-damaged woven fabric laminates.

6.2. Residual Strength Models

What all of residual strength models have in common is that they all describe strength as a monotonously degrading function of life fraction [2]. Degrieck and Paepegem [18] say that those models inherently possess a failure criterion, which is satisfied when the applied stress, or strain, equals the residual strength or the ultimate static strength [62]). Degrieck [18] identified two types of residual strength models: the *sudden death* model and the *wearout* model. The *sudden death* model is more suitable to the case of low-cycle fatigue loading, when a composite component undergoes high levels of stress. This is because, although the residual strength initially remains unchanged, it plummets in the run up to failure as the number of cycles climbs to the critical value (see Chou and Croman [79, 80]). On the other hand, in the case of high-cycle fatigue, like for wind turbine blade, the residual strength decreases more gradually as the number of load cycles increases. The *wearout* model is, in this case, more representative of the physical conditions undergone by the laminate and will be of particular interest to this review. High-cycle fatigue models are generally based on the so-called *strength-life equal rank assumption*, or SLERA, which stipulates that the strongest specimen has “either the longest fatigue life or the highest residual strength at runout [failure]” (Paepegem [18]). Hahn and Kim [67] have confirmed the validity of the assumption through a series of experiments, although in the case that multiple failure modes are occurring in concurrent of multiple failure mode, this assumption may not hold, as outlined by Sendeckyj [81].

The *wearout model* was originally introduced by Halpin *et al* [82], who assumed the residual strength function, $R(n)$ to be a monotonically decreasing function, with a power-law growth formulation as a function of the maximum cyclic stress. Based on a series of assumptions from the metal crack growth concept [18], the application of the wearout model remains valid as long as no competing failure modes are occurring throughout the fatigue life, or "even between the fatigue and static loading" (Vassilopoulos, 2004 [27]). Extensive reviews of strength degradation models are provided by Degrieck and van Paepegem [18] and Philippidis and Passipoularidis [83]. Amongst other works, we may cite those by Hahn and Kim [67, 68], Chou and Croman [79, 80], Harris [53], Yang [84], and more.

Whitworth [85] developed a modified version of the original strength degradation model introduced by Hwang and Han [62]. The more recent model [2] is rather formulated similar to Witworth formulation however an exponent is introduced as a constant C to simulate the nature of strength degradation: linear, early degradation, or 'sudden death'. Figure 8 illustrates the different cycle-by-cycle strength degradation model approaches with regards to the constant C. Nijssen provides in-depth analysis of this approach to strength-degradation modelling [2] with appropriate references.

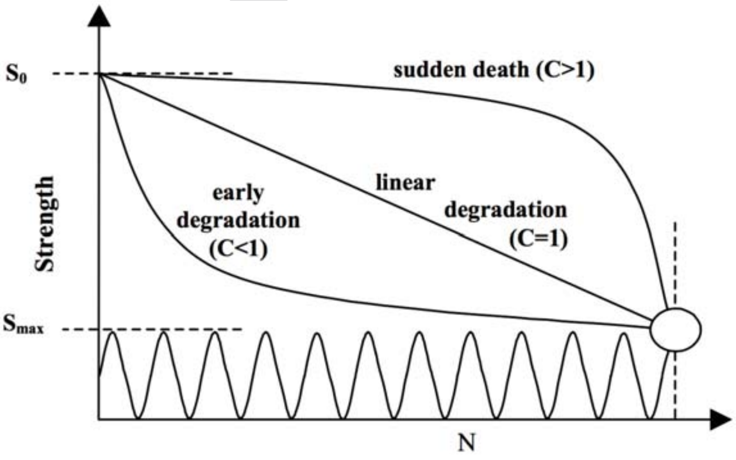

Figure 8: Comparison of Cycle-by-Cycle Degradation Models from Nijssen [2].

7. The Case of Progressive Damage Models

Often considered as the most recent works at hand, progressive damage models introduce one or more properly chosen damage variables describing the state of deterioration of the studied composite specimen or component. These models require a sound physical modelling of the underlying mechanisms of damage, often on a microscopic scale. This lead to macroscopically observable degradation of the component's mechanical properties. Degrieck and van Paepegem [18] have identified two prominent axes of research within the branch of progressive damage models: progressive models predicting damage growth (delamination size growth, crack size growth, and the like) and progressive models similar to phenomenological property degradation models, correlating mechanical property degradation with the growth of a damage parameter.

Pioneered by Kachanov in 1958, the creep damage model was originally developed for metals. It considered the description of state variables in the framework of thermodynamics of irreversible process. The model has since then been stretched beyond the limits of its applicability. While the name *continuum damage mechanics* (CDM) was apparently coined by Janson and Hult later in 1977 [86], CDM theory has been built on the belief that the material response of solids depends not only on the basic structure of the matrix but also on the characterization, distribution and growth of defects in the matrix. It is a mechanical theory used for analyzing damage and fracture processes in materials from a continuum mechanics point of view [87]. In the CDM approach, failure is not a synonym of fracture but rather refers to when an essential assumption is no longer valid in a volume [88], leading to a loss of material's integrity to sustain applied stresses.

Models for fatigue life prediction of composite materials using continuum damage mechanics have been put forward and discussed by authors such as Chaboche [88], Bhattacharya [89] or Diel [90]. Owen and Bishop [31] concluded that Paris's law was applicable to the glass-fibre-reinforced composites. This law relates the stress intensity factor range to sub-critical crack growth during fatigue.

Commonly, phenomenological damage models predicting damage growth are based on experimental testing of notched specimens in order to initiate the growth of a specific type of damage at a predetermined initiation site. Yet, despite their mechanistic approach and macro-scale scope, most phenomenological fatigue life prediction models offer efficient and simple computational implementations [60].

7.1. Progressive Property Degradation

Phenomenological models, given their often over-simplified approach, consequently fail to fully capture the seemingly missing link between damage state failure process. The need for a better understanding of intrinsic failure mechanisms led to a promising approach first developed in the 90s: progressive property degradation. This approach is based on actual damage mechanisms for specific damage types, operates at the micro-scale and accounts for ply-interaction mechanisms.

7.1.1. Matrix Cracking

At low fatigue cycles, matrix cracking (intralaminar failure mode) at interface and within the matrix is typically the first mode of failure to occur in composite materials. An important model for progressive matrix cracking was proposed by Hénaff-Gardin [91], who extensively studied the case of cross-ply laminates and put forward a propagation law.

Gamby *et al* [92] studied the process of matrix crack initiation and growth from a free edge towards the center of specimens. The experimentally tested specimens had differing architectures, namely various stacking sequences of 0° and 45° angle plies. Their research yielded a nonlinear wave equation determining crack density as a function of the number of cycles N and the distance x from a free edge of the specimen.

Another model to calculate the extent of fatigue ply-cracking was developed by Bartley-Cho *et al* [93]. They observed, in particular, that cracks initiate preferably in 90° plies compared with −45° plies. Bartley-Cho *et al* [93] introduced a failure function, where the underlying failure criterion evolves with the number of loading cycles applied to the specimen, according to an empirical relationship. Once the critical number of loading cycles is determined, the number of cycles is increased and the 90° plies crack density is determined using an empirically-fitted equation [93].

The case of damage growth due to matrix cracking in the particular case of carbon fibre-reinforced composites was covered in good part by Feng *et al* [94]. Based on experimental observations, a modified version of Paris' law was introduced for the description of an opening mode crack growth. The failure criterion states that failure occurs once the fibre strain exceeds the (critical) fibre fracture strain. From this, an estimation of the fatigue life can be made. The procedure is, however, heavily reliant on experimental data and is computationally intensive.

Matrix cracking can sometimes lead to fibre kinking. It is a failure mode characteristic that occurs when the composite is subjected to longitudinal compression. As a result, the loss of support for the fibres may eventually lead to buckling [95].

7.1.2. Fiber Failure

At higher fatigue cycles, fiber failure occurs in compression (i.e. microbuckling) or tension (i.e. accumulation of individual fibre failures up to a critical point). It is the simplest failure mode to quantify and identify. Whenever a crack is compelled to propagate in the direction normal to the fibers' alignment, fiber breakage eventually occurs and leads to global fracture of the laminate. In such cases, the fibers cracks when their fracture strain is reached [96]. Brittle fibers have a low fracture strain and hence have a low energy-absorbing capability. Authors such as Camanho [97] and Shokrieh [98] have written extensive papers regarding fiber failures criteria, thus the fiber failure modes will not be discussed in this paper.

7.1.3. Plane Shear Failure

Plane shear failure is characterised namely by in-plane/inter-laminar and out-of-plane/intra-laminar (i.e. along a ± 45° plane) mechanisms [99]. Although this failure mode does not always result in a global failure of the composite (due to the significant bending or deformations of the material), it promotes other forms of damage and ultimately leads to structural collapse [18]. Tables of failre criteria have been devised by Hashin [100], yet more recent papers attempt to incorporate nonlinear shear or matrix crack density [96].

7.1.4. Delamination Growth

Laminated composites can fail when the individual laminae debond from each other [101]. Predicting the growth of delaminations has received considerable attention in the literature. Bergmann and Prinz [102] developed a model treating the particular case of delamination growth. Later, Bucinell [103] derived a stochastic model to study the growth of free-edge delaminations in composite laminates. The growth model is derived from the principles of fracture mechanics and fits the ratio of current to critical strain energy release rate with constant parameters, which are determined using the data for delamination width vs. number of cycles for various levels of fatigue loading. However, this model is limited to the geometries experimented, namely $[\pm 45°/90°/0°]_S$ and requires further work to be fully extended to other geometries [104]. It should be highlighted that delamination is the only damage mode that can happen in between two planes.

Schon [105] put forward a simpler, more generalistic model for delamination growth damage based on a Paris Law formulation depending on experiments. The validity of the model has been successfully tested against experiments from literature. Degrieck and van Paepegem offer numerous references surrounding this focus of study [71].

7.2. Alternative Sub-Continuum Models

7.2.1. Micromechanical Models

One of the earliest stiffness reduction calculation methods based on matrix cracking is the *Shear-Lag Model* developed by Highmith and Reifsnider [106]. They observed that shear deformations in a given ply were constrained within a thin region, called shear layer or resin rich layer, around the layer interfaces between that ply and its neighbouring plies. It was noted that this region notably transferred tensile stresses in the uncracked layers to the cracked layers. From this principle, more recent stiffness-reduction approaches, such as those developed by Nuismer and Tan [107], Brillaud and El Mahi [108], Pradhan *et al*[109], Kashtalyan and Soutis [110] and Smith and Ogin [111], have been preferentially based on a finite element analyses.

An issue with micro-structural level study of composite laminate damage mechanisms is appropriately modelling of damage interaction effects, which is a major source of data discrepancy in many models. As pointed out by Degrieck [18], the trade-off is that, on the one hand, it is computationally impossible to account for all damage types on the micro-structural level, while on the other hand, homogenization of constitutive properties and taking the average of the influences of all damage mechanisms results in a loss of critical information.

Further to his initial model, Reifsnider [112] put forward a new approach, which he called the *representative volume concept*, extensively reviewed by Miller *et al* [113]. Further decomposed into critical and subcritical elements, damage initiation and propagation in the subcritical element is modelled via a mechanistic approach, while failure of the critical element is using a phenomenological approach, with local stress fields computed. Reifsnider provides an equation [112] for the calculation of strength reduction as damage progresses along with the number of loading cycles.

Halverson *et al* [114] accounted for specimen specific damage histories and correlated them with the volume damage model to predict stress-life curves. Subramanian *et al* [115] analysed the changes in tensile strength of the critical element at the composite's interface. Based on a micromechanics model, he introduced an "interface efficiency" as the main parameter estimated with experimental stiffness reduction data. As for Diao *et al* he established a statistical equation of residual strength evolution controlling the global uniaxial [116] and multiaxial [117] stiffness reduction of composite laminae.

Another model has been developed by Allen *et al* [50], which sources a mixture of micro-mechanical and phenomenological solutions to derive constitutive equations at the ply level. The constitutive equations are constructed using thermodynamics-related constraints, and depend on internal state variables. The model however makes the assumption that the composites possess fully elastic behaviour, which is certainly an idealization.

Working on the particular case of glass fibre-reinforced composites, Ogin *et al* [118] showed that crack growth rate is defined as a power function of the stored elastic energy between two neighbouring cracks in the transverse ply. Beaumont [119] furthered this concept to make a prediction of the S-N curves for composite components, by making use of the strain failure criterion. In addition, another model was proposed by Caron and Ehrlacher [120], studying micro-cracks in cross-ply composites, which is based on the assumption that "the 90° plies can be discretized in sections, which are preferential sites of cracking" [120, 18].

From the derived relationship, the residual life can be estimated, and a subsequent iterative procedure begins, in which the sections' stresses are computed and compared with the residual strength, with a constant redistribution of stresses every time a section fails. The model has been validated experimentally for the case of tension-tension fatigue in carbon/epoxy specimens. Nonetheless, the success of micro-mechanical approaches so far for fatigue life modelling is limited to single failure modes.

7.2.2. Mesomechanical Models

Another series of models work on a scale one order of magnitude up from the classic fracture micromechanics based approaches commonly seen in progressive fatigue damage models. One key reference when it comes to mesomechanical fatigue modelling is Ladevèze [121, 122], who initially directed his work toward the case of static loading of materials. It was only later extended to dynamic load modelling. Ladevèze states that composite laminates can be described by homogeneous layers in the thickness and interfaces. Consequently, by making the assumption of plane stress, the meso-level strain energy for the material may be derived. The forces associated with mechanical energy dissipation are found and a final damage evolution law is established by considering the effective stress, which takes into account the coupling between the stress and damage state involved in inelastic strains. This damage mechanics theory is originally aimed for studying the static behaviour of three-dimensional composites and laminate composites. Further discussion this method can be found in [18, 98, 121, 122].

The extension of this model to fatigue is owed to Sedrakian *et al* [123], who based their model on the one developed earlier by Ladevèze. The theory was ever limited to application in three-point bending tests, while the setup was modelled with finite elements analysis techniques. Another extension was developed by Thionnet and Renard [124, 125] in order to predict transverse cracking due to fatigue loading. Transverse cracking was modelled at meso-scale and was a function of a single scalar damage parameter, $\alpha = e/L$, defined based on physical quantities of a defect where e represents the cracked ply thickness and L represent crack spacing. In this model, cracking is driven by a crack initiation criterion dependent on thermodynamic variables.

Varna *et al* [126, 127] combined both micro-scale and meso-scale in progressive damage modelling to describe stiffness reduction as a function of static strain in cross-ply glass-fibre-reinforced epoxy laminates.

7.2.3. Generalised Residual Material Property Degradation

One of the key, reference works in progressive damage modelling has been that by Shokrieh [98] and Lessard [128, 129, 130], who developed what they call the *Generalized Residual Material property Degradation Model* for unidirectional composite laminates. The model combines three approaches, namely: (i) polynomial fatigue failure criteria determined for each mode of damage, (ii) a master curve for residual strength/stiffness, and (iii) the inclusion of arbitrary stress ratio effects via the use of Harris' normalised constant-life diagram [53], which was studied above.

The Hashin-type [44] fatigue failure criteria are determined for seven modes of damage: matrix tension, matrix compression, fibre tension, fibre compression, transverse tension, normal compression, and fibre-matrix shear. There is a criterion for each mode. For all damage modes, once failure has occurred in a ply of the laminate, the corresponding material properties are set to zero. Some of the failure modes are catastrophic and some are not. These material properties are degraded according to the so-called *Sudden Material Property Degradation Rules* [129, 130].

That said, the difference between sudden degradation and gradual degradation should be highlighted. In the case of a unidirectional ply subjected to a multiaxial state of static stress prior to the onset of sudden failure, there is no notable material property degradation, and all properties degradation of the corresponding failed ply degrade in a *sudden* fashion once the sufficient failure criteria have been satisfied. However, in the case of this same unidirectional ply subjected to state of cyclic (fatigue) stress prior to the onset of sudden failure, there is some prior, *gradual*, material property degradation. For a laminated composite subjected to cyclic loading, the strength of the plies can be higher, at first, than the stress state, until the gradual increase of the number of loading cycles and lengthening of the loading history slowly degrade the properties of the individual plies that constitute the laminate. This graduation follows what the authors call the *Gradual Material Property Degradation Rules.* Finally, after a sufficient number of loading cycles, the mechanical properties of the plies eventually hit a threshold value activating some (or all) of the failure criteria. At this point, *Sudden Material Degradation Rules* apply for final fatigue failure of the stress-tested composite laminate.

Based on this model, a computer algorithm is developed to predict the cycle-by-cycle behaviour of laminated composites subjected to fatigue. The model is tested on a pin/bolt-loaded composite plate subjected to fatigue loading conditions. Based on experimental results [130], the model shows good correlation with experimental results. In particular, the model successfully predicts the initial increase in residual strength of the composite laminate. However, for the bolt-loaded case, Shokrieh [130] argues that the significant differences between the model's predictions and experimental results lie in the definition of final failure that differs from one author to another.

Notable other authors who studied notched laminates were Beaumont and Spearing [131, 132, 133, 134, 135], who modelled the fatigue behaviour of notched carbon/epoxy cross-ply laminates. The prevailing damage mechanisms observed were: splitting in the 0° plies, delamination zones at 90° /0° ply interfaces (the size of which depended on the length of splitting), and transverse ply cracking in the 90° plies. They modelled the corresponding stiffness loss with the notion that some of the global energy, (composed of potential energy and strain energy) dissipates as the split extends, inducing a corresponding increase in compliance (stiffness decrease).

Despite the attractiveness due to novelty, progressive damage models do not incorporate multi-scale modelling; in addition, there still exists a lack of bridging between scales. The full-understanding of underlying mechanisms is yet to be developed to obtain a clear relationship between micro- and macro-scales.

8. Standards and Experiments

8.1. Standards

The testing procedure is relatively rigorous when it comes to fatigue. Processes have been matured and four major standards have surfaced, chronologically; American Society for Testing and Manufacturing (ASTM) created in 1898 [136], International Electrotechnical Commission (IEC) created in 1906 [137], International Organization for Standardization (ISO) and the more recent European Structural Integrity Society (ESIS) [138]. They specify test coupon geometries and dimensions of different tests, design requirements as well as test setup. The recommended practices include procedure for all failure criteria; tensile, compression, shear, combined-loading. Classifications are created and materials properties as well as fracture mechanics identified accordingly. Nevertheless, these tests can only identify one or two material parameters per test coupon. Furthermore, not all fracture mechanics properties are reliable [17]. Standards can be used as both a basis for design and for certification and were developed to promote international uniformity for large, small, on-shore and off-shore wind turbines. To certify a wind turbine by an international accredited registrar or classification society like Det Norske Veritas Germanischer Lloyd (DNV GL), it must be proven safe under a set of predefined load cases and tested for each of them. Two types of loads are listed: ultimate load causing instantaneous damage to the blades and fatigue loading. Regarding the latter load, most standards implement an accumulated fatigue stress analysis — with the damage parameter 'D' kept below unity (Miner's rule) — caused by stochastic forcing and evaluated over a design life of 20 years. One issue about testing procedures and certifications is about the partial safety factor, also known as a load multiplier [139, 140] and widely used in fatigue analyses. Designers can apply this conservative method to design simulation sets in order to estimate the uncertainty regarding wind loads over the long-term, thereby accounting for design conditions not properly represented by tests. However, extrapolation methods are also used for such calculations, based on standards mentionned above. Each adopt their own requirements for wind turbine blades, as analysed by [141].

8.2. *Database*

8.2.1. *Montana State University*

Important research has been carried out by the researchers in the composites team at Montana State University (MSU), in partnership with Sandia National Laboratories. Together, they conducted research dedicated to composite materials in wind turbines over a span of two decades.

The research effort populated a database maintained by MSU under the supervision of the United States Department of Energy (DOE) and Sandia National Laboratories (SNL) [2]; the DOE/MSU database . It is updated on a yearly basis and is readily available on the SNL website [142], available via *www.sandia.gov/wind.* The database predominantly gathers fatigue data for small composite coupons under a broad variety of conditions, as well as approximately 10000 static test results from 150 materials, which are mainly glass-fibre-reinforced and carbon-fibre-reinforced composite laminates, with matrix materials varying mostly between polyester, vinylester, and epoxy [143][144]. The objective of static tests and constant amplitude fatigue tests is to characterise the material properties, which then provides a framework of reference for the estimation of component fatigue life and residual strength degradation mechanics [145]. Observations from the MSU experiments [146] lead to the conclusion that classical finite element analysis-based modelling of micromechanisms of damage in laminated composites are limited in their applicability [2].

8.2.2. *FACT*

Another database, called the Fatigue of Composites for wind Turbines (FACT) database, is a product of work by De Smet and Bach [147]. Dating back to 1994, it contains results collected from a thorough literature survey process and published as an Excel spreadsheet document. Results include data for similar materials tested in different laboratories, with most materials tested being glass-fibre-reinforced composites, with some carbon-glass hybrid fibre-reinforced composites. The database also considers the effects of temperature as a variable impacting composite fatigue life. However, other than the information provided by the database, through its 1500 datapoints [147], testing conditions are rather opaque and little referencing is made to relevant related reports. Most tested laminates have undergone a manufacturing process of the hand layup type, which is prone to human error and increased irregularities, compared to automated production. With the development of OptiDAT, FACT was absorbed into the former.

8.2.3. *OPTIMAT*

The OPTIMAT project is a sizeable fatigue life research project focused on wind turbine blade materials. More details on the project's main axes of research can be found in van Wingerde *et al* [148]. All of the OPTIMAT project results are compiled into a database, called OptiDAT [149]. Failure mode was not recorded in the OptiDAT database, but rather photographs of failed coupons have been provided along with the reports. In addition, effects of humidity were investigated, highlighting a shorter fatigue life for tests performed at 100% relative humidity. Variations in manufacturing is also taken into account.

8.2.4. World-Wide Failure Exercises

As noted by Orifici [96], comparing the numerous failure criteria available in the literature is a difficult task requiring access to vast amounts of experimental data spanning the thorough range of imaginable tested loading configurations. In light of such issues, Hinton, Kaddour, and Soden [150] organised the World-Wide Failure Exercise (WWFE), which spanned 8 years, from 1996 to 2004, and compared a total of 19 leading failure models for the analysis of 14 plane stress test configurations involving a wide array of materials, laminates, and loading configurations. According to the organisers, the purpose of the exercises was to help the developers of the various composite fatigue and general failure models to provide a "true and unambiguous interpretation of their own work" [151], thereby preventing third party interpretation.

Failure criteria were ranked in a number of different categories, including prediction accuracy, data-fitting requirement level, and generality. A notable out-come of the WWFE has been the identification of five "promising" failure prediction outcomes: Puck [152], Cuntze [153] and Tsai [49]. Two further exercises have been organised since.

8.3. WISPER Load Sequence and Variations

The Wind turbine Reference Spectra, or WISPER is a standardised spectrum loading sequence for wind turbines aiming to reproduce in a laboratory what the composite material will experience on a wind turbine blade. The load sequence is usually fixed and scalable, so that it may be reproduced in laboratories and at different scales. Standardised load sequences such as this one serve to test all components in the same manner and thus rank them fairly with respect to their usability for a certain application. As outlined by Nijssen [2], although such tests are not actual design spectra, their purpose is to reproduce, as accurately as possible, the loading environment experienced by the material in action. Figure 9 [2] compares the existing wind turbine reference spectra, with the green horizontal line representing zero load.

The predefined and fixed WISPER testing load sequence consists of a series of integers from 1 to 64, which indicate points of load reversal. There are 265,423 points, which constitute 132,711 load cycles. The levels range from 24 to 39, with the level 25 indicating zero loading. The WISPER levels are subjected to a gain (multiplier) in order to model the desired maximum load level. The maximum peak in the WISPER load sequence is rather large, and is the cause of most failures during testing.

Further, to cut WISPER testing a time, a new version, WISPERX, was introduced, where the X refers to the fact that the new version incorporates ten times as few cycles as the original load sequence. Indeed, WISPERX differs with WISPER by removing all cycles which have an amplitude of 8 levels or less, resulting in approximately 13,000 cycles [2]. For constant frequency testing, this effectively divides the testing time by a factor of ten. The WISPERX spectrum has, however, been considered by some researchers to be obsolete since the measurements used to synthesise the spectrum were taken from turbines that were much smaller than more modern ones. As the trend has been for wind turbines to progressively increase in dimensions, a new version of the loading sequence, called NEW WISPER, was devised. The process and results are analysed exhaustively by Bulder *et al* [154] and Söker *et al* [155]. In addition, since the WISPERX sequence is mainly tensile, it would be interesting to revert it in order to obtain a loading sequence for compressive testing (RWISPERX). Overall, the availability of multiple load spectra does not mitigate the testing load for a material under study. In addition, Nijssen [2] points out that ranking materials does not necessarily require multiple standards. Should a set a composites need to be ranked for a particular design, with a specific time constraint, it would perhaps most efficient to determine the predominant expected load spectrum for this component before choosing the appropriate available load sequence.

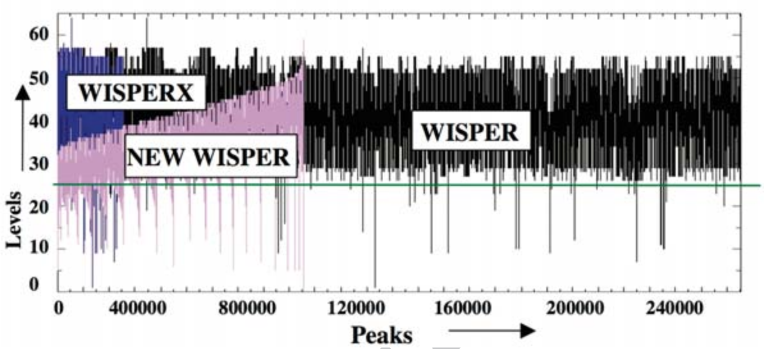

Figure 9: Wind Turbine Reference Spectra [2].

9. Discussions and Conclusion

9.1. Challenges of Fatigue Modelling

Figure 10 displays all fatigue models discussed previously in chronological order. The years presented do not represent the year of publication of all individually sub-models within any given category; they rather show an average of the publication years of all reviewed papers per category. It can be observed that fatigue modelling is still a very recent preoccupation and that significant efforts have been made since the early 70s to establish concepts for new models.

Fong [156] states two reasons behind the difficulty and price tag related to fatigue modelling: the multi-scale nature of damage mechanisms and the uniqueness of each specimen's properties, response, and features (no two specimens can be strictly *identical*). According to Fong, some of the drawbacks of fatigue damage modelling are:

- Scale confusion: information from measurements on different scales (atomic, sub-grain, grain, and specimen levels) is combined improperly and leads to erroneous results.
- Ill-supported generalisations: models may often apply to a specific case and attempt a generalisation to a broader set of loading environments, specimens, or regimes. For example, as in [157] stiffness reduction is often dividable into three regimes: (i) sharp initial reduction, (ii) gradual decrease, and (iii) final failure; yet related models are often found to be valid in some stages and invalid in others.

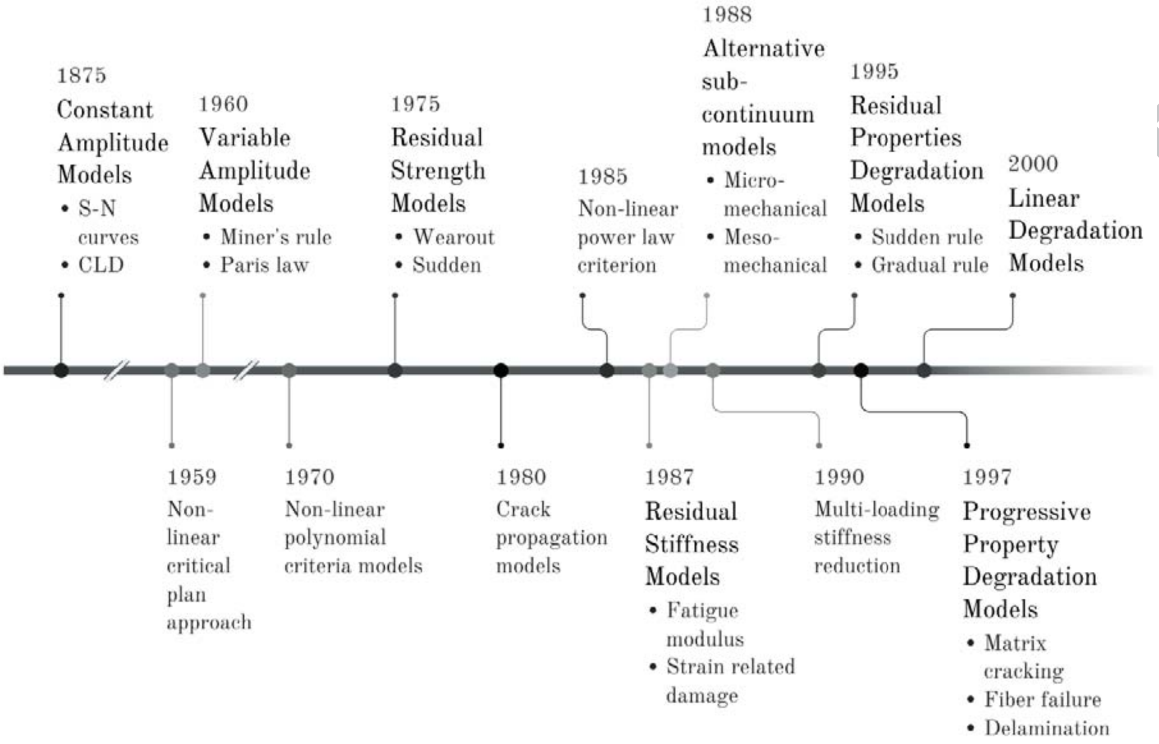

Figure 10: Timeline of fatigue models' elaboration

- Oversimplification: curve fitting of experimental data is done by using oversimplified expressions [158]. Barnard [158] evidenced that much of the scatter of the S-N curve drawn from his experimental data was a result of a change in failure mode, which generated a discontinuity in the S-N curve.

It should also be noted that amongst the models covered, many of them were established for specific cases. In particular, they were based on experiments using laminates with specific boundary conditions, stacking sequences and subjected to simplified cyclic loading history (constant amplitude, constant frequency). As a result, it is difficult for current modelling software to thoroughly account for all possible operating conditions of wind turbine blades in their environments. Indeed, while cracks and their propagation can be modelled in the early design stages thanks to different models such as the ones explained in Chapter 4,5,6 and 7, exact crack development and resulting impact on lifespan cannot be accurately estimated due to the vagaries of the environment. Florian [159] has organised a maintenance decision framework in order to optimize blade lifetime with maintenance planning and argues that modelling is an important issue. Regarding small scale wind turbines, they require more maintenance than their larger counterparts, essentially due to their higher fatigue cycles. Nevertheless, as they share some intrinsic similarities, the same fatigue models can be used to estimate their fatigue life.

As mentioned previously, phenomenological models are the most popular models in industry but not in research. One domain of investigation aims at reducing the computational cost of progressive damage models.

Yet, while progressive damage models are indeed more computationally expensive than their phenomenological counterparts, accurately quantifying that difference in cost often has often proved challenging. Unearthed literature regarding cost reduction has approached the topic from a qualitative standpoint. Perfect computational performance is of course unrealistic: it is computationally impossible to account for all interactions of all damages at the micro-structural level [18, 160]. [161].

Again, generalisations are often difficult to thoroughly construct. According to Barnard [158], some of the underlying reasons are:

– Load history is an important factor in considering damage evolution. The order in which block loading sequences are applied has a significant impact on damage growth. Low-to-high loading leads to matrix-cracking and delamination while the opposite leads to fibre failure [2]. In simulations, stochastic models are used to reproduce a realistic load history while, in reality, little has been discussed about the techniques used to retrieve the load history. Nonetheless, widespread approach such as fluid-structure interaction analysis or simple data analysis are used.

– The residual strength and fatigue life of composite laminates decrease more rapidly when the loading sequence is repeatedly changed after just a few loading cycles, according to Farrow [162]. This is called the “cycle-mix effect” and demonstrates that for constant total number of cycles, the fatigue life of tested serviced laminates with smaller cycled loading blocks is shorter than that of laminates with larger blocks in their load history.

– The role of loading frequency is significant, according to Ellyin and Kujawski [163]. It is especially the case for laminates with dominating matrix volume fraction and matrix loading that frequency becomes important due to the matrix’s sensitivity to rate of loading and internal heat generation (with temperature rise) [163].

– The predominant mode of damage is different at different stress states [158], and failure patterns consequently vary with cyclic stress level and even with number of cycles to failure.

– Finally, most experiments are carried out in simple loading conditions, namely uniaxial stress conditions in tension or compression, which are quite simplistic in light of the more complex nature of real loads applied to the structures when in service.

In the case of block-loading tests, an important sequence effect was revealed, where the low/high (LH) load sequence yielded comparatively more ply cracks than its high/low (HL) counterpart. In the case of a HL sequence, there is significant fibre failure and a resulting drastic decrease in strength. In a LH sequence, substantial matrix cracking leads to macroscopic delamination. However, given the non-dependence of the model on load history, the sequence effect could not be predicted for block fatigue loading of any type.

In recent years, publications about wind turbine blades have been mainly focusing on two streams: better incorporation of climate-related (environmental) factors on one hand, and expanding (and even unifying) existing models on the other hand. In the first stream, environmental components include, for example, impact fatigue analysis caused by "collisions" with rain droplets or hail stones. Amirzadeh has released two papers focused on rain-induced erosion in wind turbine blades. The first [164] presents the development of a stochastic rain simulation model that would calculate the drop impact pressure in time and space to obtain a profile of expected erosion lifetime of the coating. Amirzadeh's second paper [165] looks at implementing the previously developed rain model using the Finite Elements method to determine transient stress within blade coating. The model also simulates the onset of surface roughening and estimates fatigue stress-life accordingly. Other authors have focused their research on the assessment of existing damage models. Caous [166] has researched the ply scale damage model as an alternative to the classical metal-based models widely used for composite material structures; the traditional normative approach is compared with a progressive fatigue damage model at ply-level. He concluded that, unlike the former linear model, the latter allowed damage zone identification and its evolution in time. Westphal [167], in the same vein, has validated CLD formulations with three different load spectra, Wisper, WisperX and NewWisper2. Readers must keep in mind that the ultimate objective is to understand the early stages of degradation, which have a drastically negative effect on wind turbine performance.

The main goal of all damage models developed to date is life prediction accuracy. Experimental works have underlined the lack of validity of many models in practice, be they empirical or conceptual damage/fracture mechanics models. Widespread empirical fatigue models are commonly used by international guidelines such as Germanischer-Lloyd GL and often based on empirical data from metals. They can be viewed as an articulated method, with a series of sub-elements that need to be solved in order to reach a final solution. As a result, the accuracy of the model will depend on the accuracy of each of its sub-components. As for the progressive models, they build their accuracy on top of that of their empirical counterparts.

9.2. Conclusions

Almost all fatigue life estimation models are linked back to experimental data and S-N formulation employed [168]. Extending experimental coupon-based results (and their subsequent fatigue models) to the case of fatigue behaviour of full-size structural components (i.e. wind turbine blades) is a challenge of its own kind.

Constant amplitude testing provides a useful starting point for fatigue analysis of wind turbines. However it does not nearly constitute a sufficient approach for the practical design of wind turbines. Indeed, due to the wide known variety of loading undergone by wind turbines, it is doubtful that forces acting on wind turbine blades will be, on average, constant throughout their twenty years of service. Thus, the spectral load response has to be tested. As outlined by Degrieck [18], since the vast majority of the fatigue models have been developed for and applied to a specific composite material and specific stacking sequence, it is very difficult to assess to which extent a particular model can be applied to another material type than the one for which it was tested.

One major issue with fatigue-life models is their reliance on available S-N curve data and related CLD formulations. With each model seems to come a new formulation, or fatigue life data interpretation methodology, which has resulted in significant discrepancy between seemingly similar models. As a result, a recurring point of criticism that arises to question such models is their inherent subjectivity, as it is never perfectly clear why a particular set of data-fitting parameters or parameter values was chosen over another. In addition, Nijssen [2] has provided an extensive discussion on the limitations of S-N curve and CLD utilisation as well as the drawbacks of experimental equipment used to conduct the tests. Furthermore, manufacturers most of the times cannot wait for a long period of time in order to get experimental data, hence this is why spectrum analysis are being developed and put forward as the main solution.

Non-linear models usually account for multiaxial and multiplane stress fields, as well as provide better fit with experimentally extracted material data.

Progressive damage accumulation models that connect material properties with types of loading cases seem to be the way forward with corresponding implementation in numerical software. Stress redistribution and scale length issues of meso- and macro-scales are discussed. Between ply-to-ply and structures level analysis, the latter is favoured by many authors. Loading histories remain a concern as the composite will not adopt the same failure modes if the structure is loaded from low-to-high or high-to-low amplitudes. Further studies need to be performed to reach a general fatigue model. An attempt has been made World-Wide Failure Exercise (WWFE) to propose general failure criteria for composites but is rather limited.

References

[1] Boyer H., et al. Atlas of Fatigue Curves. ASM International; 1986.

[2] Roger N. Fatigue life prediction and strength degradation of wind turbine rotor blade composites. Ph.D. thesis; TU Delft; 2006.

[3] Brøndsted P., Nijssen R.P. Advances in wind turbine blade design and materials. Elsevier; 2013.

[4] Mandell J.F., Reed R.M. Fatigue of Fiberglass Wind Turbine Blade Materials. Sandia National Laboratory Contractor Report: SAND92-7005; 1992.

[5] Van Delft D., de Winkel G., Joosse P., van Delft D., de Winkel G., Joosse P. Fatigue behaviour of fibreglass wind turbine blade material under variable amplitude loading. In: 35th Aerospace Sciences Meeting and Exhibit. 1997, p. 951.

[6] Sutherland H.J. Frequency domain analysis of the fatigue loads on typical wind turbine blades. Journal of solar energy engineering1996;118(4):204–11.

[7] Kensche C., Seifert H. Wind turbine rotor blades under fatigue loads. In: Developments in the Science and Technology of Composite Materials. Springer; 1990, p. 173–80.

[8] Ragheb M. Wind turbines in the urban environment. Retrieved July2008;12:2009.

[9] Riziotis V.A., Voutsinas S.G. Fatigue loads on wind turbines of different control strategies operating in complex terrain. Journal of Wind Engineering and Industrial Aerodynamics2000;85(3):211–40.

[10] Mouzakis F., Morfiadakis E., Dellaportas P. Fatigue loading parameter identification of a wind turbine operating in complex terrain. Journal of Wind Engineering and Industrial Aerodynamics1999;82(1-3):69–88.

[11] Lange C.H. Probabilistic fatigue methodology and wind turbine reliability. Tech. Rep.; Sandia National Laboratory report: SAND96-1246; 1996.

[12] Mishnaevsky Jr L., Favorsky O. Composite materials in wind energy technology. Thermal to Mechanical Energy Conversion: Engines and Requirements, EOLSS2012;50(2):195–207.

[13] Ashwill T. Materials and innovations for large blade structures: research opportunities in wind energy technology. In: 50th AIAA Structures, Structural Dynamics and Materials Conference, Palm Springs, CA, USA. 2009, p. 2407.

[14] Grand J.A. Wind power blades energize composites manufacturing. Plastics technology2008;54(10):68–75.

[15] Bian J. Fiberglass composite tensile fatigue resistance: fiber surface damage analysis and fatigue resistant fiber coating. Master's thesis; Montana State University-Bozeman, College of Engineering; 1996.

[16] Gamstedt E.K., Andersen S.I. Fatigue degradation and failure of rotating composite structures–materials characterisation and underlying mechanisms. Tech. Rep.; Risø Report; 2001.

[17] Kaminski M., Laurin F., Maire J., Rakotoarisoa C., Hémon E. Fatigue damage modeling of composite structures: the onera viewpoint. 9; 2015, p. p–1.

[18] Degrieck J., Van Paepegem W. Fatigue damage modeling of fibre-reinforced composite materials. Applied mechanics reviews2001;54(4):279–300.

[19] Bathias C. An engineering point of view about fatigue of polymer matrix composite materials. International journal of fatigue2006;28(10):1094–9.

[20] Weeton J.W., Thomas K.L., Peters D.M. Engineers' Guide to Composite Materials. American Society for Metals; 1987.

[21] Sutherland H.J. A summary of the fatigue properties of wind turbine materials. Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology2000;3(1):1–34.

[22] Cairns D., Mandell J.F., Samborsky Fatigue of composite materials and substructures for wind turbine blades. Tech. Rep.; Sandia National Labs., Albuquerque, NM (US); Sandia National Labs., Livermore, CA (US); 2002.

[23] Mandell J., Samborsky D., Cairns D. Advanced wind turbine blade structure development program at montana state university. In: 35th Aerospace Sciences Meeting and Exhibit. 1997, p. 952.

[24] Jang Y.J., Choi C.W., Lee J.H., Kang K.W. Development of fatigue life prediction method and effect of 10-minute mean wind speed distribution on fatigue life of small wind turbine composite blade. Renewable Energy2015;79:187–98.

[25] Park T., Kim M., Jang B., Lee J., Park J. A nonlinear constant life model for the fatigue life prediction of composite structures. Advanced Composite Materials2014;23(4):337–50.

[26] Lloyd G. Rules and Regulations, IV-Non-marine Technology, Part 1-Wind Energy. Germanischer Lloyd; Hamburg; 2003.

[27] Philippidis T.P., Vassilopoulos A.P. Life prediction methodology for gfrp laminates under spectrum loading. Composites Part A: applied science and manufacturing2004;35(6):657–66.

[28] Ryder J., Walker E. Ascertainment of the effect of compressive loading on the fatigue lifetime of graphite epoxy laminates for structural applications. Tech. Rep.; DTIC Document; 1976.

[29] Fawaz Z., Ellyin F. Fatigue failure model for fibre-reinforced materials under general loading conditions. Journal of composite materials1994;28(15):1432–51.

[30] Post N., Case S., Lesko J. Modeling the variable amplitude fatigue of composite materials: A review and evaluation of the state of the art for spectrum loading. International Journal of Fatigue2008;30(12):2064–86.

[31] Owen M., Bishop P. Prediction of static and fatigue damage and crack propagation in composite materials. In: Advisory Group for Aerospace Research and Development AGARD, Failure modes of composite materials with organic matrices and their consequences on design. 1974, p. 15–24.

[32] Lampman S.R. ASM Handbook, Vol. 19: Fatigue and Fracture. ASM International; 1996.

[33] Hertzberg R.W. Deformation and Fracture Mechanics of Engineering Materials. Wiley; 1977.

[34] Sutherland H.J. On the fatigue analysis of wind turbines. Tech. Rep.; Sandia National Labs., Albuquerque, NM (US); Sandia National Labs., Livermore, CA (US); 1999.

[35] Wahl N.K. Spectrum fatigue lifetime and residual strength for fiberglass laminates. Ph.D. thesis; Montana State University-Bozeman, College of Engineering; 2001.

[36] Philippidis T., Vassilopoulos A. Fatigue strength prediction under multiaxial stress. Journal of Composite Materials1999;33(17):1578–99.

[37] Miyano Y., Nakada M., Kudoh H., Muki R. Prediction of tensile fatigue life for unidirectional cfrp. Journal of composite materials2000;34(7):538–50.

[38] Miyano Y., McMurray M.K., Enyama J., Nakada M. Loading rate and temperature dependence on flexural fatigue behavior of a satin woven cfrp laminate. Journal of Composite Materials1994;28(13):1250–60.

[39] Andersons J., Korsgaard J. The effect of stress ratio on durability and damage accumulation in grp at uniaxial loading. In: International Conference on Fatigue of Composites. 1997, p. 3–5.

[40] Freebury G., Musial W. Determining equivalent damage loading for full-scale wind turbine blade fatigue tests. In: 2000 ASME Wind Energy Symposium. 2000, p. 50.

[41] Kazacoks R., Jamieson P. Evaluation of fatigue loads of horizontal up-scaled wind turbines. Energy Procedia2015;80:13–20.

[42] Pérez-Campuzano D., Gómez de las Heras-Carbonell E., Gallego-Castillo C., Cuerva A. Modelling damage equivalent loads in wind turbines from general operational signals: Exploration of relevant input selection methods using aeroelastic simulations. Wind Energy2018;21(6):441–59.

[43] Petermann J., Plumtree A. A unified fatigue failure criterion for unidirectional laminates. Composites Part A: Applied Science and Manufacturing2001;32(1):107–18.

[44] Hashin Z., Rotem A. A fatigue failure criterion for fiber reinforced materials. Journal of composite materials1973;7(4):448–64.

[45] Reifsnider K., Gao Z. A micromechanics model for composites under fatigue loading. International Journal of Fatigue1991;13(2):149–56.

[46] Tan H., Huang Y., Liu C., Geubelle P. The mori–tanaka method for composite materials with nonlinear interface debonding. International Journal of Plasticity2005;21(10):1890–918.

[47] Wu C.L. Thermal and mechanical fatigue analysis of cfrp laminates. Composite Structures1993;25(1-4):339–44.

[48] Jen M.H., Lee C.H. Strength and life in thermoplastic composite laminates under static and fatigue loads. part i: Experimental. International journal of fatigue1998;20(9):605–15.

[49] Tsai S.W., Wu E.M. A general theory of strength for anisotropic materials. Journal of composite materials1971;5(1):58–80.

[50] Allen D., Harris C., Groves S. A thermomechanical constitutive theory for elastic composites with distributed damage -— i. theoretical development. International Journal of Solids and Structures1987;23(9):1319–38.

[51] Adam T., Gathercole N., Reiter H., Harris B. Life prediction for fatigue of t800/5245 carbob-fibre composites: Ii. variable-amplitude loading. International Journal of Fatigue1994;16(8):533–47.

[52] Gathercole N., Reiter H., Adam T., Harris B. Life prediction for fatigue of t800/5245 carbon-fibre composites: I. constant-amplitude loading. International Journal of Fatigue1994;16(8):523–32.

[53] Harris B. Fatigue behaviour of polymer-based composites and life prediction methods. Durability Analysis of Structural Composite Systems, AH Cardon (Ed), Balkema, Rotterdam1996;1:49–84.

[54] Ellyin F., El-Kadi H. A fatigue failure criterion for fiber reinforced composite laminae. Composite Structures1990;15(1):61–74.

[55] Bond I. Fatigue life prediction for grp subjected to variable amplitude loading. Composites Part A: Applied Science and Manufacturing1999;30(8):961–70.

[56] Xiao X. Modeling of load frequency effect on fatigue life of thermoplastic composites. Journal of Composite Materials1999;33(12):1141–58.

[57] Findley W.N. A theory for the effect of mean stress on fatigue of metals under combined torsion and axial load or bending. 6; Engineering Materials Research Laboratory, Division of Engineering, Brown University; 1958.

[58] Brown M.W., Miller K. A theory for fatigue failure under multiaxial stress-strain conditions. Proceedings of the Institution of Mechanical Engineers1973;187(1):745–55.

[59] Glinka G., Shen G., Plumtree A. A multiaxial fatigue strain energy density parameter related to the critical fracture plane. Fatigue & Fracture of Engineering Materials & Structures1995;18(1):37–46.

[60] Van Kuik G., Peinke J. Long-term research challenges in wind energy-a research agenda by the European Academy of Wind Energy; vol. 6. Springer; 2016.

[61] Reifsnider K., Talug A. Analysis of fatigue damage in composite laminates. International Journal of Fatigue1980;2(1):3–11.

[62] Hwang W., Han K. Cumulative damage models and multi-stress fatigue life prediction. Journal of Composite Materials1986;20(2):125–53.

[63] Hwang W., Han K.S. Fatigue of composites — fatigue modulus concept and life prediction. Journal of Composite Materials1986;20(2):154–65.

[64] Kam T., Chu K., Tsai S. Fatigue reliability evaluation for composite laminates via a direct numerical integration technique. International journal of solids and structures1998;35(13):1411–23.

[65] Kam T., Tsai S., Chu K. Fatigue reliability analysis of composite laminates under spectrum stress. International journal of solids and structures1997;34(12):1441–61.

[66] Fatemi A., Yang L. Cumulative fatigue damage and life prediction theories: a survey of the state of the art for homogeneous materials. International journal of fatigue1998;20(1):9–34.

[67] Hahn H., Kim R. Proof testing of composite materials. Journal of Composite Materials1975;9(3):297–311.

[68] Hahn H., Kim R.Y. Fatigue behavior of composite laminate. Journal of Composite Materials1976;10(2):156–80.

[69] O'Brien T.K., Reifsnider K.L. Fatigue damage evaluation through stiffness measurements in boron-epoxy laminates. Journal of composite materials1981;15(1):55–70.

[70] Sidoroff F., Subagio B. Fatigue damage modelling of composite materials from bending tests. In: Sixth International Conference on Composite Materials (ICCM-VI) & Second European Conference on Composite Materials (ECCM-II); vol. 4. Elsevier London, UK; 1987, p. 4–32.

[71] Paepegem W.v., Degrieck J. Numerical modelling of fatigue degradation of fibre-reinforced composite materials. In: Computational techniques for materials, composites and composite structures. Civil-Comp Press; 2000, p. 319–26.

[72] Van Paepegem W., Degrieck J. Experimental set-up for and numerical modelling of bending fatigue experiments on plain woven glass/epoxy composites. Composite structures2001;51(1):1–8.

[73] Whitworth H. A stiffness degradation model for composite laminates under fatigue loading. Composite structures1997;40(2):95–101.

[74] Brøndsted P., Andersen S.I., Lilholt H. Fatigue damage accumulation and lifetime prediction of gfrp materials under block loading and stochastic loading. In: 18th Risø International Symposium on Materials Science, Polymeric Composites - Expanding the Limits. Roskilde, Denmark, Risø International Laboratory; 1997, p. 269–78.

[75] Brøndsted P., Lilholt H., Andersen S. Fatigue damage prediction by measurements of the stiffness degradation in polymer matrix composites. In: 8th International Spring Meeting of International Conference on Fatigue of Composites. ICFC; 1997, p. 370–7.

[76] Yang J., Jones D., Yang S., Meskini A. A stiffness degradation model for graphite/epoxy laminates. Journal of Composite Materials1990;24(7):753–69.

[77] Lee L., Fu K., Yang J. Prediction of fatigue damage and life for composite laminates under service loading spectra. Composites science and technology1996;56(6):635–48.

[78] Hansen U. Damage development in woven fabric composites during tension-tension fatigue. Journal of Composite Materials1999;33(7):614–39.

[79] Chou P.C., Croman R. Residual strength in fatigue based on the strength-life equal rank assumption. Journal of Composite materials1978;12(2):177–94.

[80] Chou P., Croman R. Degradation and sudden-death models of fatigue of graphite/epoxy composites. In: Composite Materials, Testing and Design (Fifth Conference). Philadelphia: ASTM International; 1979, p. 431–54.

[81] Sendeckyj G. Fitting models to composite materials fatigue data. In: Test methods and design allowables for fibrous composites. ASTM International; 1981, p. 245–60.

[82] Halpin J.C., Jerina K.L., Johnson T.A. Characterization of composites for the purpose of reliability evaluation. In: Analysis of the test methods for high modulus fibers and composites. ASTM International; 1973, p. 5–64.

[83] Philippidis T., Passipoularidis V. Residual static strength of fibrous composites after fatigue: a literature survey. Tech. Rep.; OB_TG5_R001_UP rev. 000; 2002.

[84] Yang J.N. Fatigue and residual strength degradation for graphite/epoxy composites under tension-compression cyclic loadings. Journal of Composite Materials1978;12(1):19–39.

[85] Whitworth H. Evaluation of the residual strength degradation in composite laminates under fatigue loading. Composite Structures2000;48(4):261–4.

[86] Janson J., Hult J. Fracture mechanics and damage mechanics- a combined approach. In: International Congress of Theoretical and Applied Mechanics, 14 th, Delft, Netherlands, Aug. 30-Sept. 4; vol. 1. 1977, p. 69–84.

[87] Krajcinovic D. Continuous damage mechanics revisited: basic concepts and definitions. Journal of Applied Mechanics1985;52(4):829–34.

[88] Chaboche J.L. Continuum damage mechanics: Part ii—damage growth, crack initiation, and crack growth. Journal of applied mechanics1988;55(1):65–72.

[89] Bhattacharya B., Ellingwood B. Continuum damage mechanics analysis of fatigue crack initiation. International journal of fatigue1998;20(9):631–9.

[90] Diel S., Huber O. A continuum damage mechanics model for the static and cyclic fatigue of cellular composites. Materials2017;10(8):951.

[91] Hénaff-Gardin C., Lafarie-Frenot M.C., Goupillaud I. Prediction of cracking evolution under uniaxial fatigue loading in cross-ply composite laminates. In: International Conference on Fatigue of Composites. La Société Française de Métallurgie et de Matériaux; 1997, p. 189–96.

[92] Gamby D., Hénaff-Gardin C., Lafarie-Frenot M.C., Tahiri V. A model for damage growth in aeronautical composite laminates subjected to tensile fatigue loading. In: International Conference on Fatigue of Composites. La Société Française de Métallurgie et de Matériaux; 1997, p. 386–92.

[93] Bartley-Cho J., Lim S.G., Hahn H.T., Shyprykevich P. Damage accumulation in quasi-isotropic graphite/epoxy laminates under constant-amplitude fatigue and block loading. Composites Science and Technology1998;58(9):1535–47.

[94] Feng X., Gilchrist M.D., Kinlock A.J., Matthews F.L. Development of a method for predicting the fatigue life of cfrp composites. In: International Conference on Fatigue of Composites. La Société Française de Métallurgie et de Matériaux; 1997, p. 407–14.

[95] Pinho S., Darvizeh R., Robinson P., Schuecker C., Camanho P. Material and structural response of polymer-matrix fibre-reinforced composites. Journal of Composite Materials2012;46(19-20):2313–41.

[96] Orifici A., Herszberg I., Thomson R. Review of methodologies for composite material modelling incorporating failure. Composite structures2008;86(1-3):194–210.

[97] Davila C.G., Camanho P.P., Rose C.A. Failure criteria for frp laminates. Journal of Composite materials2005;39(4):323–45.

[98] Shokrieh M. Progressive fatigue damage modelling of composite materials. Master's thesis; McGill University; 1996.

[99] Daniel I. Failure mechanisms in fiber-reinforced composites1978;.

[100] Hashin Z. Fatigue failure criteria for unidirectional fiber composites. ASME, Transactions, Journal of Applied Mechanics1981;48:846–52.

[101] Canturri C., Greenhalgh E.S., Pinho S.T., Ankersen J. Delamination growth directionality and the subsequent migration processes–the key to damage tolerant design. Composites Part A: Applied Science and Manufacturing2013;54:79–87.

[102] Bergmann H., Prinz R. Fatigue life estimation of graphite/epoxy laminates under consideration of delamination growth. International Journal for Numerical Methods in Engineering1989;27(2):323–41.

[103] Bucinell R. Development of a stochastic free edge delamination model for laminated composite materials subjected to constant amplitude fatigue loading. Journal of Composite Materials1998;32(12):1138–56.

[104] Bui V., Iannucci L., Robinson P., Pinho S. A coupled mixed-mode delamination model for laminated composites. Journal of Composite Materials2011;45(16):1717–29.

[105] Schön J. A model of fatigue delamination in composites. Composites Science and Technology2000;60(4):553–8.

[106] Highsmith A.L., Reifsnider K.L. Stiffness-reduction mechanisms in composite laminates. In: Damage in Composite Materials: Basic Mechanisms, Accumulation, Tolerance, and Characterization. Philadelphia, PA: ASTM International; 1982, p. 103–17.

[107] Nuismer R., Tan S. Constitutive relations of a cracked composite lamina. Journal of Composite Materials1988;22(4):306–21.

[108] Brillaud J., El Mahi A. Numerical simulation of the influence of stacking sequence on transverse ply cracking in composite laminates. Composite Structures1991;17(1):23–35.

[109] Pradhan B., Kumar N.V., Rao N. Stiffness degradation resulting from 90 ply cracking in angle-ply composite laminates. Composites science and technology1999;59(10):1543–52.

[110] Kashtalyan M., Soutis C. Stiffness degradation in cross-ply laminates damaged by transverse cracking and splitting. Composites Part A: Applied Science and Manufacturing2000;31(4):335–51.

[111] Smith P., Ogin S. On transverse matrix cracking in cross-ply laminates loaded in simple bending. Composites Part A: Applied Science and Manufacturing1999;30(8):1003–8.

[112] Reifsnider K.L. The critical element model: a modeling philosophy. Engineering Fracture Mechanics1986;25(5-6):739–49.

[113] Miller H., Reifsnider K., Stinchcomb W., Ulman D., Bruner R. Cumulative damage model for advanced composite materials. Tech. Rep.; GENERAL DYNAMICS FORT WORTH TX FORT WORTH DIV; 1984.

[114] Halverson H.G., Curtin W.A., Reifsnider K.L. Fatigue life of individual composite specimens based on intrinsic fatigue behavior. International Journal of Fatigue1997;19(5):369–77.

[115] Subramanian S., Reifsnider K., Stinchcomb W. A cumulative damage model to predict the fatigue life of composite laminates including the effect of a fibre-matrix interphase. International Journal of Fatigue1995;17(5):343–51.

[116] Diao X., Ye L., Mai Y.W. A statistical model of residual strength and fatigue life of composite laminates. Composites science and technology1995;54(3):329–36.

[117] Diao X., Lessard L.B., Shokrieh M.M. Statistical model for multiaxial fatigue behavior of unidirectional plies. Composites science and technology1999;59(13):2025–35.

[118] Ogin S., Smith P., Beaumont P. Matrix cracking and stiffness reduction during the fatigue of a (0/90) s gfrp laminate. Composites Science and Technology1985;22(1):23–31.

[119] Beaumont P. The mechanics of fatigue damage in structural composite materials. In: Developments in the Science and Technology of Composite Materials. Springer; 1990, p. 195–205.

[120] Caron J., Ehrlacher A. Modeling of fatigue microcracking kinetics in crossply and experimental validation. In: International Conference on Fatigue of Composites. 1997, p. 3–5.

[121] Ladeveze P. A damage approach for composite structures: Theory and identification. In: Mechanical Identification of Composites. Proceedings of the European Mechanics Colloquium. Springer; 1991, p. 44–57.

[122] Ladeveze P. A damage computational method for composite structures. Computers & Structures1992;44(1-2):79–87.

[123] Sedrakian A., Ben Zineb T., Billoet J., Bobet V. Fatigue behavior simulation of industrial composite parts. In: Proceedings of the 2nd International Conference on the Fatigue of Composites. 2000, p. 4–7.

[124] Thionnet A., Renard J. Laminated composites under fatigue loading: a damage development law for transverse cracking. Composites science and technology1994;52(2):173–81.

[125] Thionnet A., Renard J. Modeling of fatigue behaviour in composite laminates. In: Proceedings of the 12th International Conference on Composite Materials. 1999, p. 363.

[126] Varna J., Joffe R., Talreja R. A synergistic damage-mechanics analysis of transverse cracking in [$\pm\theta$/904] s laminates. Composites Science and Technology2001;61(5):657–65.

[127] Varna J., Krasnikovs A., Kumar R.S., Talreja R. A synergistic damage mechanics approach to viscoelastic response of cracked cross-ply laminates. International Journal of Damage Mechanics2004;13(4):301–34.

[128] Shokrieh M.M., Lessard L.B. Residual fatigue life simulation of laminated composites. In: International Conference on Advanced Composites(ICAC 98), Hurghada, Egypt. 1998, p. 79–86.

[129] Shokrieh M.M., Lessard L.B. Multiaxial fatigue behaviour of unidirectional plies based on uniaxial fatigue experiments —- i. modelling. International Journal of Fatigue1997;19(3):201–7.

[130] Shokrieh M.M., Lessard L.B. Multiaxial fatigue behaviour of unidirectional plies based on uniaxial fatigue experiments —- ii. experimental evaluation. International journal of fatigue1997;19(3):209–17.

[131] Beaumont P.W.R., Spearing S.M. Development of fatigue damage mechanics for application to the design of structural composite components. In: Mechanical identification of composites. Proceedings of the European Mechanics Colloquium. Elsevier; 1990, p. 311–26.

[132] Spearing S.M., Beaumont P.W. Fatigue damage mechanics of composite materials. part i: Experimental measurement of damage and post-fatigue properties. Composites Science and Technology1992;44(2):159–68.

[133] Spearing S., Beaumont P. Fatigue damage mechanics of composite materials. part iii: Prediction of post-fatigue strength. Composites science and technology1992;44(4):299–307.

[134] Spearing S., Beaumont P., Ashby M. Fatigue damage mechanics of composite materials. part ii: A damage growth model. Composites Science and Technology1992;44(2):169–77.

[135] Spearing S., Beaumont P., Smith P. Fatigue damage mechanics of composite materials. part iv: Prediction of post-fatigue stiffness. Composites science and technology1992;44(4):309–17.

[136] ASTM Standard practices for cycle counting in fatigue analysis. The American Society for Testing and Materials E1049-85, Philadelphia1997;3(1):710–8.

[137] IEC 61400-1 edition 3: Wind Turbines. Standard of the International Electrotechnical Commission; 2014.

[138] Aubin V., Quaegebeur P., Degallaix S. Cyclic behaviour of a duplex stainless steel under multiaxial loading: Experiments and modelling. European Structural Integrity Society2003;31:401–22.

[139] Moriarty P. Safety-factor calibration for wind turbine extreme loads. Wind Energy2008;11:601–12.

[140] Veers P., Butterfield S. Extreme load estimation for wind turbines-issues and opportunities for improved practice. In: 20th 2001 ASME Wind Energy Symposium. 2001, p. 44.

[141] Musial W.D., Butterfield C.P. Using partial safety factors in wind turbine design and testing. National Renewable Energy Laboratory; 1997.

[142] Mandell J.F., Samborsky D.D. Doe/msu composite material fatigue database: test methods, materials, and analysis. Tech. Rep.; Sandia National Labs., Albuquerque, NM (United States); 1997.

[143] Samborsky D.D. Fatigue of e-glass fiber reinforced composite materials and substructures. Master's thesis; Montana State University; 1999.

[144] Mandell J.F., Samborsky D.D., Sutherland H.J. Effects of materials parameters and design details on the fatigue of composite materials for wind turbine blades. Nice, France; 1999, p. 628–33.

[145] Samborsky D.D., Mandell J.F. Fatigue resistant fiberglass laminates for wind turbine blades. Wind Energy1996;:46–51.

[146] Mandell J., Samborsky D., Combs D., Scott M., Cairns D. Fatigue of composite material beam elements representative of wind turbine blade substructure. Tech. Rep.; National Renewable Energy Lab., Golden, CO (US); 1998.

[147] De Smet B., Bach P.W. Database FACT: Fatigue of composites for wind turbines. Netherlands Energy Research Foundation ECN-C-94-045; 1994.

[148] van Wingerde A., van Delft D., Janssen L., Philippidis T.P., Brøndsted P., Dutton A., et al. Optimat blades: results and perspectives. In: Scientific Proceedings of the European Wind Energy Conference and Exhibition. Citeseer; 2006, p. 69–72.

[149] Nijssen R. Optidat–fatigue of wind turbine materials database2006;URL: `www.kc-wmc.nl/optimat_blades`.

[150] Hinton M.J., Kaddour A.S., Soden P.D. Failure Criteria in Fibre Reinforced Polymer Composites. Elsevier; 2004.

[151] Kaddour A., Hinton M., Li S., Smith P. The world-wide failure exercises: How can composites design and manufacture communities build their strength. In: Proceedings of the 16th European Conference on Composite Materials (ECCM16), Seville, Spain. 2014, p. 22–6.

[152] Puck A., Schürmann H. Failure analysis of frp laminates by means of physically based phenomenological models. In: Failure Criteria in Fibre-Reinforced-Polymer Composites. Elsevier; 2004, p. 832–76.

[153] Cuntze R., Freund A. The predictive capability of failure mode concept-based strength criteria for multidirectional laminates. Composites Science and Technology2004;64(3-4):343–77.

[154] Bulder B., Peeringa J., Lekou D. New wisper - creating a new standard load sequence from modern wind turbine data. Tech. Rep.; OPTIMAT report doc. no. 10278; 2005.

[155] Soker H., Kaufeld N. New wisper - creating a new load sequence from modern wind turbine data. Tech. Rep.; OPTIMAT report; 2004.

[156] Fong J. What is fatigue damage? In: Damage in Composite Materials: Basic Mechanisms, Accumulation, Tolerance, and Characterization. ASTM International; 1982, p. 243–66.

[157] Schulte K., Baron C., Neubert N. Damage development in carbon fibre epoxy laminates: cyclic loading. 1985.

[158] Barnard P., Butler R., Curtis P. Fatigue scatter of ud glass epoxy, a fact or fiction? In: Composite Structures 3. Springer; 1985, p. 69–82.

[159] Florian M., Sørensen J.D. Wind turbine blade life-time assessment model for preventive planning of operation and maintenance. Journal of Marine Science and Engineering2015;3(3):1027–40.

[160] Amaya P. Progressive damage and failure model for composite laminates under multiaxial loading conditions. Ph.D. thesis; The Ohio State University; 2012.

[161] Främby J. On efficient modelling of progressive damage in composite laminates using an equivalent single-layer approach. Ph.D. thesis; Department of Applied Mechanics, Chalmers University of Technology; 2016.

[162] Farrow I.R. Damage accumulation and degradation of composite laminates under aircraft service loading: assessment and prediction. Master's thesis; Cranfield Institute of Technology; 1989.

[163] Ellyin F., Kujawaski D. Fatigue testing and life prediction of fibreglass-reinforced composites. 1992, p. 111–7.

[164] Amirzadeh B., Louhghalam A., Raessi M., Tootkaboni M. A computational framework for the analysis of rain-induced erosion in wind turbine blades, part i: Stochastic rain texture model and drop impact simulations. Journal of Wind Engineering and Industrial Aerodynamics2017;163:33–43.

[165] Amirzadeh B., Louhghalam A., Raessi M., Tootkaboni M. A computational framework for the analysis of rain-induced erosion in wind turbine blades, part ii: Drop impact-induced stresses and blade coating fatigue life. Journal of Wind Engineering and Industrial Aerodynamics2017;163:44–54.

[166] Caous D., Bois C., Wahl J.C., Palin-Luc T., Valette J. Toward composite wind turbine blade fatigue life assessment using ply scale damage model. Procedia engineering2018;213:173–82.

[167] Westphal T., Nijssen R. Fatigue life prediction of rotor blade composites: Validation of constant amplitude formulations with variable amplitude experiments. In: Journal of Physics: Conference Series; vol. 555. IOP Publishing; 2014, p. 012107.

[168] Sendeckyj G.P. Life prediction for resin-matrix composite materials. In: Composite materials series; vol. 4. Elsevier; 1991, p. 431–83.