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The history of fiber-reinforced polymer composite laminate fatigue

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ABSTRACT

Investigations of the fatigue performance of composite materials have accompanied their introduction in several engineering domains since the 1950s. An abundance of publications have emerged dealing with the experimental investigation of the fatigue performance of composites under different loading and environmental conditions, as well as the development of theories for the modeling of the fatigue behavior and/or prediction of the fatigue life of the materials systems under consideration. This work aims to briefly review and present the history of fiber-reinforced polymer composite laminate fatigue investigations, dividing the last 70 years into three periods. The early 1950–1975 period, when the "new" materials and their behavior under (simple) fatigue loading patterns were discovered. The mature, 1975–2000 period, when more loading and material parameters were investigated and the basic theoretical background was established. And finally, the later period, in the new millennium, when more detailed experimental campaigns were performed (assisted by developments in a multitude of engineering and scientific fields) and parameters that had previously been overlooked by researchers were taken into account.

1. Introduction

Fatigue was identified as a critical loading pattern long ago by the scientific community [1]. The first manuscript where fatigue was referred to is probably the book written in 1841 by Jean-Victor Poncelet, a French mathematician and mechanical engineer. In that book, entitled "Introduction à la méchanique industrielle physique ou expérimentale" Poncelet mentioned that any spring subjected to push-pull force would eventually break under a load far smaller than the static breaking load [2]. Jean-Victor Poncelet was the first to coin the term fatigue to describe this phenomenon. In the English language, the term was introduced in 1854 by the British engineer F. Braithwaite in his paper "On the fatigue and consequent failure of metals" in the proceedings of the Institution of Civil Engineers (ICE) [2]. Several experimental campaigns were performed in the UK in the following years to investigate the phenomenon, mainly due to unexpected failures of railway axles.

Nevertheless, it was well before this, in 1829, when the German mining engineer W. A. S. Albert carried out the first fatigue tests on metallic conveyor chains [3,4] and reported his observations. Subsequently, numerous failures that could not be explained by known theory were attributed to fatigue loading. With the development of the railways, in the mid-19th century, the failure of wagon axles was such a frequent occurrence that it attracted the attention of engineers. Between 1852 and 1870 a German engineer, August Wöhler, conducted the first extended experimental program on the fatigue of metallic materials, [3]. This program comprised full-scale fatigue tests on wagon axles but also specimen tests under cyclic loading patterns of tensile, bending and torsional loads. Wöhler constructed a test rig on which he could test wagon axles under bending moments that were developed by loads suspended from the ends of the axles. The developed stresses (S) were recorded together with the number of rotations up to failure (N). The results were drawn on the S–N plane to formulate the first S–N curve, which, however, was restricted to the representation of experimental data, without proposing any mathematical formulation to describe this behavior. It was only in 1910 when Basquin [5] proposed a power law equation to define an S-N curve to simulate the performance of the available S-N data. This same equation is basically still used today, both for metals and composites. It is clearly an empirical equation, fitting the experimental behavior of the material concerned. Nevertheless, Freudenthal, in 1946 [6], argued that "The relation expresses the effect of a general mechanism of fatigue and is more than purely empirical (best fit line of large number of observations) as suggested by the circumstance that it is valid for practically any kind of material, whatever its deformational performance".

The short introduction above shows that fatigue has been the subject of intensive investigations for almost 200 years and, despite the progress made, fatigue failures continue to occur [7] (see for example the derailment of the ATSB 9T90 train in 2017). Those first attempts to analyze the fatigue behavior of materials and structures were based on

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the experience with constructions operating under real loading conditions. Everything that is loaded, even if the loads are low, has a finite life. It is well documented that a major percentage of structural failures happen due to fatigue or fatigue-related phenomena [8,9]. Most of them are unexpected failures due to defects on the microscale that cannot be identified and do not present any indication, such as a measurable property reduction prior to failure. According to Freudenthal fatigue can be considered "…as an essential statistical effect of happenings on a submicroscopic level" [6]. Fatigue theory is basically empirical/phenomenological; the process of the initiation of microcracks that finally will form macroscopic cracks in the material is not taken into account specifically in the relevant equations. The fatigue properties should therefore be analyzed statistically due to the large variations exhibited during testing.

Numerous experimental programs have been conducted over recent decades for the characterization of the fatigue behavior of several structural materials of that particular time. As technology developed and new test frames and measuring devices were invented, it became far easier to conduct complex fatigue experiments and measure the properties and characteristics of materials, of structural components, even of full scale structures. As a result, almost all failure modes were identified and many theoretical models have been established for modeling and eventually predicting the fatigue life of several different material systems. Significant support has been provided by the new monitoring and damage identification techniques, such as Digital Image Correlation (DIC) [10] and x-ray tomography (see for example Chapter 16 of [1]). Nevertheless, fatigue theories, even today, are basically empirical. Fatigue model equations dealing with damage and remaining life are, literally, "fitted" to existing experimental data from material/component testing in order to calibrate their parameters and produce reliable simulation of the exhibited behavior and/or prediction of the fatigue life under different loading conditions or material configurations.

Investigations of the fatigue behavior of composite materials were initiated together with their introduction as structural elements in several engineering applications, back in the 1950s, with a few technical reports, e.g. [11] and technical notes, e.g. [12] date back to the 40 s. As early as 1955 Hulbert [13] mentioned that "fatigue and creep are such important aspects of dynamic and static behavior that, among the welter of data accumulated around reinforced plastics materials, it is astonishing to find little or nothing published about either property". However, for Hulbert, the main problem lay in the "welter of data" signifying the inconsistency of the existing data (for several reasons, including specimen preparation and new problems arising during fatigue testing of composites) that result in less confidence in fiber- reinforced materials for primary structures. Almost 20 years later, Harris [14] wrote, "The abundance of experimental data does not contribute to our understanding about the fatigue of composites, and there is not yet (in 1977) any general agreement about what kind of design data are most useful for reinforced polymers". Reinforced polymers (then known as reinforced plastics) are inhomogeneous, anisotropic, and rarely behave in a linear elastic fashion. Crack initiation and propagation is not a single and simple process as it is in metals and crack paths are highly complex with the crack itself not being the sole manifestation of structural damage. Since the early days of fatigue investigations of composites it was revealed that they exhibit several modes of damage including delamination, matrix crazing, fiber failure, void growth, matrix cracking, and composite cracking. A particular structure may exhibit any or all of these damage modes and it is difficult to predict, a priori, which mode will dominate and cause failure. Therefore, although all the damage occurring in a composite material could be identified, it was extremely difficult to accurately quantify its effect on the fatigue life [15]. According to Salkind [15], it is risky to design fatigue structures for fatigue loading based on time to fracture, as composites generally exhibit property changes very early in their fatigue life, prior to fracture, and such changes in elastic properties could lead to structural failure long before the structure is in danger of fracturing.

Although composite materials are designated as fatigue insensitive, especially when compared to metallic ones, they also fail under fatigue loads. The basic concept of composite fatigue is no different than that of metals, but rather more complicated [16]. The introduction of composite materials in a wide range of applications obliged researchers to consider fatigue when investigating a composite material, and engineers to realize that fatigue effects are important and must be considered in calculations during design processes. Initially, composites were used as replacements for previous "conventional" materials such as steel, aluminum or wood, and later as "advanced" materials allowing engineers to adopt a different approach to design problems, propose alternative design concepts (based on the free formability and light weight characteristics of composites) and redesign structures. Unfortunately, although the physics of fatigue are the same, the fatigue behavior of composite materials is different to that of metallic ones [15,17]. Fatigue failure of composites is challenging to analyze, as many damage mechanisms interact. This is not only true for multidirectional and textile composites, but also for unidirectional laminates [16]. Therefore, methods already developed and validated for the fatigue life modeling and prediction of "conventional" materials cannot be directly applied to composite materials. Moreover, the large number of different material configurations resulting from the multitude of fibers, matrices, manufacturing methods, lamination stacking sequences, etc. makes the development of a commonly accepted method to cover all these variances difficult. As mentioned by Bathias in [18] "obviously, it is difficult to get a general approach of the fatigue behavior of composite materials including polymer matrix, metal matrix, ceramic matrix composites, elastomeric composites, Glare, short fiber-reinforced polymers and nano–composites".

One way of dealing with composite material fatigue is to undertake extended experimental programs and then develop analytical, mathematical, expressions to model fatigue life and be able to reproduce experimental results. Probably the first large experimental campaign aiming to characterize the fatigue behavior of several different composite material systems (different fibers and matrices) was performed by K. H. Boller between ca. 1950–1965, see [17,19,20]. These works came after the few performed in the 1940s such as the publication on the fatigue behavior of wood and glued wood structures in 1946 [21], and the technical note of 1948 [12], that compared the mechanical properties of five laminated plastics and concluded that glass-fabric laminate had the most desirable properties of all those measured (including quasi-static tension, compression, torsion, long-term creep tests, under different stresses in tension, fatigue of notched and unnotched specimens, fatigue in bending at different temperatures – -60 °C, 25 °C, 70 °C – and fatigue tests in torsion). Boller's works include fatigue experimental results from composite laminates made from numerous resins (epoxides, polyesters, phenolics) with a variety of reinforcements (asbestos or glass mat, glass fabric, unwoven glass fibers) in different orientations showed S-N curves without an obvious fatigue limit. During the last 70 years a great many publications concerning the fatigue performance of polymer composite materials have been presented, with the number of new publications increasing each year. Nevertheless, even with this logarithmic increase of available experimental data, and the potential for more detailed and complicated experimental campaigns thanks to the developments in machines, measuring devices and equipment, the scientific and engineering communities has not yet reached an agreement regarding the most appropriate fatigue data to be collected (as Harris suggested in [14] back in 1977)!

Some of the experimental programs conducted refer to specific materials, and have been mainly designed to assist the development of theoretical models, e.g. [22–26], while others, like those presented in [27,28], are more extensive and cover a wide range of materials for specific applications, in this case, materials for wind energy. Only lately were experimental programs developed to extensively investigate specific loading cases, such as the creep-fatigue interaction in composites (e.g. [29–33]), or the two-dimensional fatigue crack propagation in laminates and sandwich structures (e.g. [34]). Moreover, research was conducted to cover newly introduced concepts and materials, such as 3D printed composites [35,36], and the fatigue behavior of thick- [37,38] and thin-ply composite laminates [39,40]. Along with the aforementioned experimental work, a considerable number of theories emerged to model the fatigue behavior of the examined composites and consequently predict their behavior under unknown loading conditions, e.g. [41–45]. The behavior of composite materials is known to be sensitive to the loading pattern due to their cyclic- and time-dependent mechanical properties [30,31]. The time-dependent mechanical properties are related to the rheological deformation of the material when it is subjected to an external load while the cyclic–dependent mechanical properties are mainly attributed to the damage formation and accumulation [31,46,47]. The time- and cyclic-dependent mechanical properties of laminated composites usually interact, and the degree of interaction depends on the loading spectrum and material, [29,32,48–50]. In continuous fatigue, the interaction between the time- and cyclic- dependent mechanical properties was studied by monitoring the evolution of fatigue hysteresis loops [29,32,49,51] assigning the shift of the fatigue hysteresis loops to cyclic creep effects and the slope of the loops to degradation of the fatigue stiffness due to damage [29]. The interaction between the time- and cyclic-dependent mechanical properties was also studied by applying more complicated loading patterns in which continuous-fatigue was interrupted in different ways [30–32,52,53]. Interruption of cyclic loading could also change the fatigue life depending on the applied stress level and material type, as was presented in [30,31]. Vieille et al. [32] showed that fatigue life could be extended with prior creep in angle-ply carbon/PPS thermoplastic composite depending on the loading conditions at temperatures higher than the glass transition temperature (Tg). Similarly, it was shown that sustained periods of static loads have significant retardation effects on damage propagation and extended fatigue life of an angle-ply thermoset graphite/epoxy composite system [52]. Recently, it was shown that the effect of creep on the fatigue life of angle-ply thermoset laminates could be positive or negative depending on the applied stress level and hold time [31].

A literature search (www.scopus.com) with keywords “fatigue” and “composites” in the disciplines “Engineering”, “Materials science”, “Energy”, and “Multidisciplinary” produces more than 19,000 research articles in the field, with more than 90% of them published after 1980, and around 400 articles per year after 1995, and an average of ca. 800 per year since 2010 [1]. This immense increase shows, among other things, the great interest of researchers, engineers, and industry in this field. Nevertheless, it must be borne in mind that many published research findings could present erroneous results for several reasons, as described in [54], as well as the fact that a percentage (higher or lower depending on the field of research) of scientific outputs could be intentionally/unintentionally falsified, leading to scientific misconduct as described in [55]. According to [54] the fewer the studies conducted in one particular scientific field, the less likely the research findings are to be true. The same applies for the smaller effect sizes (e.g. marginal changes in material behavior due to a loading or environmental effect in the case of material engineering) as well as the greater flexibility in designs, definitions and expected outcomes. The border between data fabrication and “cooking” and unintentional presentation of false scientific results is very vague, since the urge to make ordinary observations appear more accurate and significant (definition of data “cooking” already since 1830 [56]) forces scientist to publish results without sufficient support from experimental evidence and validated assumptions.

Despite this explosive production of scientific publications in the field, even if those with illegitimate or erroneous results are excluded, countless topics remain unresolved in the domain of composite fatigue. Typical areas requiring further investigation concern the S–N and constant life diagram formulations for the interpretation of existing fatigue data, non-linear damage accumulation rules that can take load sequence effects into account, cycle-counting methods that do not scramble the load sequence of the applied load time series, consideration of non-proportional stress components in biaxial/multiaxial loading cases, the exploitation of material behavior at very low and very high cycle regimes, the development of methods that take into account the stochastic nature of the fatigue phenomenon, etc. The successful elaboration of all these areas based on well-founded principles and sound approaches for the interpretation of the behavior of the examined materials at different scales and the development of rigorous methods to bridge scales (from micro to full scale) and to implement, in life prediction processes, parameters that have been hitherto neglected by researchers, would allow the development of reliable procedures to appropriately address composite fatigue.

Researchers have attempted to tackle these and other topics in order to model and/or predict the fatigue behavior of composite materials of interest. However, the terms “modeling” and “prediction” have often been misused (even abused following the previous discussion of scientific result falsification [54,55]), usually by adopting the term “prediction” when “modeling” is performed. As well explained in [57] (although not based on data from works in engineering science) there is a clear difference between the (statistical) modeling for causal explanation, descriptive modeling, and predictive modeling. Modeling, either explanatory (causal) or descriptive, is used to fit observed material behaviors and possibly attempt to describe the observations. Regarding composite fatigue, fracture mechanics modeling or micromechanical approaches (e.g. [58,59]) can be assumed as being typical examples of explanatory/causal modeling. Descriptive modeling is the more “premature”, aiming at summarizing or representing the data structure in a compact manner. Unlike explanatory modeling, in descriptive modeling any underlying causal theory is absent. Typical examples are the so-called phenomenological modeling approaches, with the most common ones being S-N curve equations, derived by traditional, e.g. [60] or even new methods [61,62]. On the other hand, predictive modeling can be defined as the process of applying a (statistical) model or data mining algorithm for the purpose of predicting new or future observations –i.e., reproduce data that have not been used for the model development. Predictive modeling can be based either on phenomenological, such as the fatigue failure criteria, e.g. the Hashin criterion [41] or the FTPF [63], or physically-based modeling fatigue theories such as those based on specific damage metrics such as fatigue stiffness or residual strength [64–66], or the fracture mechanics-based approaches [67,68]. The term “prediction” should be used when extrapolation is performed outside the existing database in terms of prediction of the behavior of the same material under new loading conditions, e.g. spectrum loading based on constant amplitude fatigue data [69,70], or extension of the modeling to low- or high-cycle fatigue regimes, when data exist in the range between, e.g. 10^3–10^6 cycles, or even prediction of the behavior of other material systems based on models derived for a specific material (see e.g. [71,72]).

Over the years, definitions changed, plastics became polymers, it was decided to use the term “S-N” curve instead of Wöhler curve for composites etc. In the reviewed publications the nomenclature could be slightly different, nevertheless, the basic fatigue terminology together with a representative S-N curve and a typical constant life diagram (CLD) annotation, that will be discussed in detail in the following sections of this article, are presented in Figs. 1–3.

A typical stress (strain) time series is presented in Fig. 1, annotated by the basic parameters used to characterize the fatigue loading. A cyclic stress is applied between defined maximum and minimum cyclic stresses, while the ratio of the minimum over the maximum cyclic stress is defined as the stress ratio, usually represented by R. The testing frequency, f, indicates how many cycles the material undergoes per second. Fatigue loading can be either of constant amplitude, or

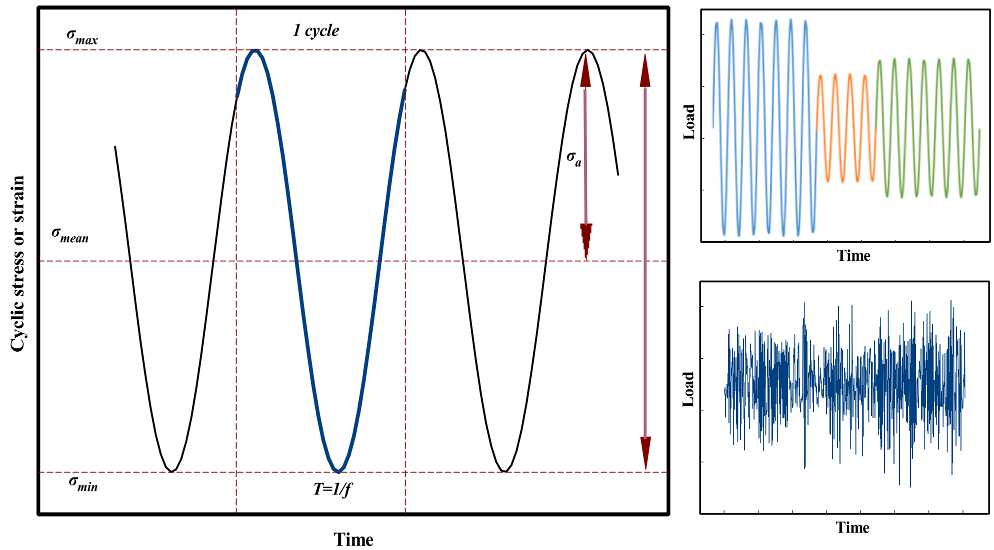

Fig. 1. Basic fatigue terminology, constant amplitude, block loading and variable (irregular) loading time series [1].

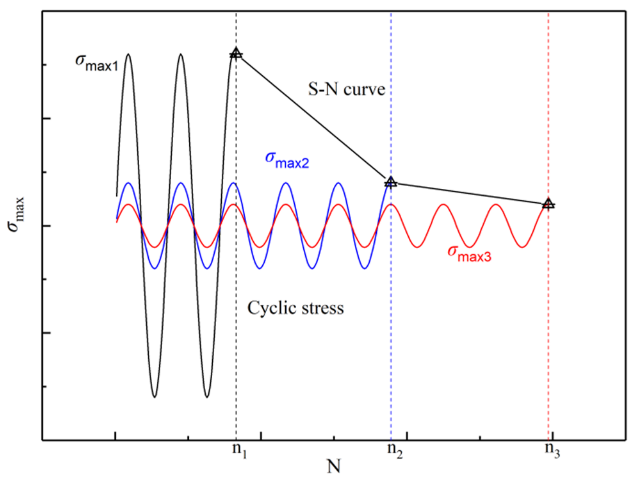

Fig. 2. Schematic representation of S-N curve derivation [4].

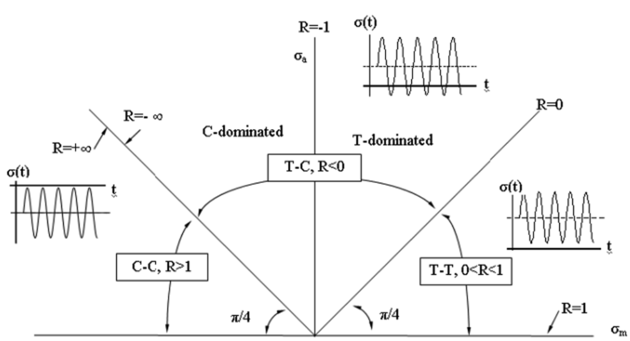

Fig. 3. Typical CLD annotation [45].

comprised of more complicated block and variable amplitude profiles as also shown in Fig. 1.

The method for estimating S-N curves based on constant amplitude fatigue data is schematically shown in Fig. 2. For the demonstration, three different tests were selected, each corresponding to a different stress level and therefore resulting in different numbers of cycles to failure, indicated by symbols. As expected, the lower the stress level, the longer the fatigue life of the examined material. An S-N curve is a line simulating the experimentally derived fatigue behavior and can be derived by interpolation between the collected fatigue data results in the S-N curve of the material under the selected fatigue conditions - R–ratio, frequency, environment etc. The debate concerning the representation of the constant amplitude fatigue data that began a century ago, with Basquin's equation, back in 1910, and as described in the following is still alive and well today.

Constant life diagrams reflect the combined effect of mean stress and material anisotropy on the fatigue life of the examined composite material. Furthermore, they offer a predictive tool for the estimation of the fatigue life of the material under loading patterns for which no experimental data exist. The main parameters that define a CLD are the mean cyclic stress, σ_m, cyclic stress amplitude, σ_a, and R-ratio. A typical constant life diagram is presented in Fig. 3.

A historical review of investigations regarding the fatigue performance of (polymer) composite materials, and more specifically the experimental campaigns, that helped to establish sufficient knowledge for the modeling of the fatigue of polymer composites is presented in the following sections. The article presents a historical review of the main steps/milestones of the research in composite material fatigue and discusses the current state of the art. It is an exemplary and not an exhaustive literature review – this would need much more space – as it focuses mainly on the description of the key experimental investigations of each period and the basic relevant theoretical deterministic approaches, without addressing research on fracture mechanics approaches or experimental work investigating environmental effects on composite fatigue behavior.

2. Early (first) composite fatigue investigations (1950–1975)

Literature review places the first fatigue investigations for composite materials as early as their implementation in several engineering applications, back in the 1950s. Research publications of that era are mainly descriptive, attempting to discover the response of composite laminates to fatigue loading patterns, principally of constant amplitude, e.g. [17,19]. When scientists and engineers of that time obtained sufficient experience with these new materials and understood the basic mechanisms of their fatigue failure, (between 1965 and 1975) they started performing experimental campaigns aiming to explain (causal modeling) the observed phenomena and link them to damage development in the examined materials, see for example [15,73]. These first years were exploratory; a significant part of the research efforts was allocated to the examination of the feasibility of using fiber-reinforced composite materials in primary structural applications, and was usually published in reports instead of scientific publications, see e.g. [74]. The research findings were presented in terms of pure experimental results, usually by investigating large numbers of specimens to derive statistically valid conclusions. Nevertheless, as early as 1967, see [74], it was realized that relatively few tests of greater depth rather than the more common approach of studying a statistically valid and larger sample where each specimen receives less attention and consequently yields less information, could be more appropriate to derive sound conclusions concerning the fatigue performance of FRPs.

Engineers and scientists did not yet have a clear idea of which parameters should be investigated, which were those having an important effect on the fatigue performance of polymer composite materials [75]. Nevertheless, it was been very soon realized that composite materials offer substantial improvements over metals for application to structures subject to fatigue loadings [13], comprising components subjected to dynamic loads, such as rotor heads and blades are designed on the basis of high cycle fatigue, and fiber composites offer considerably better fatigue properties than metals [76]. These first fatigue studies proved that the testing of (anisotropic) composite materials is even more complicated than that of homogeneous materials. Boller [16,17,19,77] summarized his research findings in the following– which by the way can be found, verbatim , or slightly rephrased, in an abundance of publications since then, e.g. [15,19]: "The basic concept of fatigue of composites is not different from that for metals, but rather more complicated. This is due principally to the anisotropic structure of composite materials, presenting a problem in load transfer from one strong link to another through a weak link" [16]. It has been well established that the continual application of stresses, either alternating, steady, or a combination of both, causes the failure of fiber-reinforced composite laminates even though the stress is less than the short-time static ultimate stress, such as in metals, and he stated that "fatigue of FRP under cyclical load conditions is complicated by most of the usual parameters which influence the fatigue of metals, plus a great number of other parameters due to the structure-like aspect of composites" [79].

In an early publication [77] K. H. Boller presented the results obtained from fatigue testing on laminates made with numerous resins and a variety of reinforcements at different orientations showing that, generally, and in contrast to metals, the S-N curves for the laminates show no obvious fatigue limit [73]. Nevertheless, research on carbon fiber-reinforced polymers [80] showed no fatigue failures observed at stress levels below 70% of the mean static strength of the specimens, and therefore, CFRP materials were designated as fatigue- resistant materials, showing less steep S-N curves than those derived for GFRP laminates. The work of Boller [77], and others, e.g. [16,79–82] pointed out the need for standardization procedures for composite fatigue testing. However, initially it was assumed that certain fatigue testing methods for metals (e.g. BS 3518, [78]) especially those relating to definitions, data presentation, direct stress testing, and statistical analysis, could be appropriate for fatigue investigations of composites.

The effect of fiber and matrix configurations on the fatigue performance of GFRP composite laminates between a thousand and 10 million cycles has been examined in [17,19], and is probably the first available experimental campaign of this type. Six standard and four heat-resistant (polyester, epoxy, phenolic and silicone) resins were used, reinforced by glass fabrics and glass woven fabrics. The experimental results were presented in 53 S-N curves, showing the effects on fatigue strength of notching, moisture in fabrics, resins, the mean stress levels, the angles to wrap, as well as the effect of temperature up to ca. 260 °C (500°F). The test frequency was 15 Hz (referred to as 900 cycles per minute in that publication) and no investigation of the frequency effect on fatigue strength was reported. Frequency effects were investigated in [74] for axial and bending experiments on GFRP laminates under different loading conditions (tension-tension (T-T) – $R = 0.05$, fully reversed loading, $R = -1$, and compression-compression (C-C) fatigue loading, $R = 10$) and at frequencies between 0.1 and 30 Hz (6, 50 and 1800 cycles per minute in [74]). Frequency effects appear to be related to the compressive portion of the loading pattern. Observation of the derived S-N curves showed that there is no appreciable effect under tensile axial fatigue conditions, while a small effect was observed under fully reversed loading, and slightly greater effect under the bending and axial compressive cyclic loadings. This effect was attributed in [74] to the hysteresis loop that appears while loading/unloading polymer composites. Additional studies presented during the following years (see next section) partially validate these remarks.

The effect of the matrix is very significant, with epoxies found to be the most appropriate for fatigue [15,17]. The effect of fiber orientation has not yet been clarified since it is quite complex [15]. Although in quasi-static loading it is obvious that the on-axis direction (fibers at 0°) is optimal, in fatigue the unidirectional configuration is not necessarily the best, probably because the unidirectional material is subject to splitting and rapid crack propagation in the matrix parallel to the fibers [15]. This could also be the reason for the low fatigue strength of high modulus composites at zero mean stress (even more pronounced in this case due to the compressive loads) as observed initially in [83] for boron-reinforced aluminum. The off-axis fatigue behavior has been thoroughly investigated by Owen and co-workers and presented in a series of publications, e.g. [79–82,84,85]. Off-axis loading of anisotropic composite laminates can cause multiaxial stress states (referred to as complex stress states in [81]) in the material principal coordinate system, see Fig. 4. An inconsistency between results obtained for thin-walled tubular specimens and prismatic laminates was observed, indicating the need for additional research on this topic.

These first works [16,17,19,20,74,78] also revealed the mean stress effect on the fatigue behavior of polymer composites. Boller [19,20] introduces, perhaps for the first time in the literature, the constant life diagram (CLD) concept for composites and shows that the allowable stresses obtained by a modified Goodman line could be too high, thus demonstrating that the Goodman diagram might be too conservative when used for composites. This is in contradiction to the findings of Cornish et al. [86] who suggested that the effect of the mean stress on the compression-compression fatigue behavior in low-cycle fatigue is similar to that on metals, i.e., the Goodman diagram is approximately linear [15]. In these first representations of Boller, it is also suggested that the constant life lines for composites are non-linear, while the entire diagram is shifted (usually to the right – the tensile part), see Fig. 5, since most of the fiber reinforced-composites are stronger in tension than in compression, assumptions/suggestions confirmed by several subsequent investigations as shown in the following sections.

After this first period, by 1970, scientists already knew almost everything about failure modes, damage mechanisms, and material behavior [15] (almost as much as we know today!). It was common

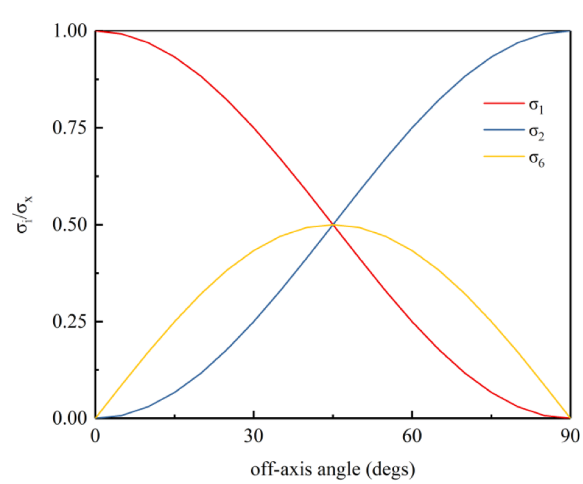

Fig. 4. Multiaxial stress state at principal coordinate system for off-axis layer.

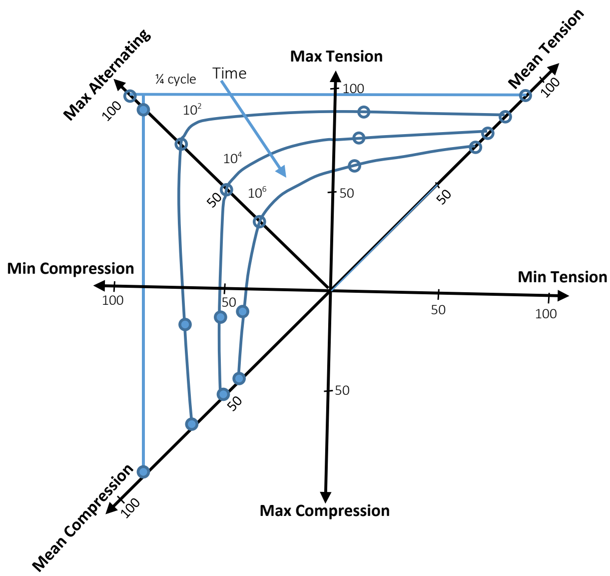

Fig. 5. Typical constant life diagram for composites according to [16].

knowledge that composites exhibit several damage modes including delamination, matrix crazing, fiber failure, void growth, matrix cracking, and composite cracking. A particular structure may exhibit any or all of these damage modes and it is difficult to predict, a priori, which mode will dominate and cause failure. Therefore, although all damage that occurs in a composite material can be identified, it is extremely difficult to accurately quantify its effect on fatigue life. According to [15], it is risky to design structures for fatigue loading based on time to fracture, as composites generally exhibit property changes very early in their fatigue life, before fracture. Such changes in elastic properties could lead to structural failure long before the structure is in danger of fracturing.

The difference between the damage evolution in a composite and that in a metal structure is depicted schematically in Fig. 6 [76]. Metal parts exhibit cracks when they begin to fail in fatigue, and the cracks generally propagate in a predictable manner to failure. Fatigue damage in composites consists of resin crazing (matrix failure), fiber debonding, delamination, fiber cracking, or composite cracking either separately or in combination, and the predominance of one or more is highly dependent on the laminate orientations and loading conditions. In addition, crack propagation often does not occur in a predictable manner, as is the case for metals, but often changes direction due to the material anisotropy. In addition, the joints and attachments used for composite structures often result in failure modes different from those typified by the laminate itself. Indeed, composite cracking may compose only a small part of the fatigue life at the very end, but all the earlier indications can certainly be made good use of. Based on the limited experience acquired, it was expected that composite materials would be

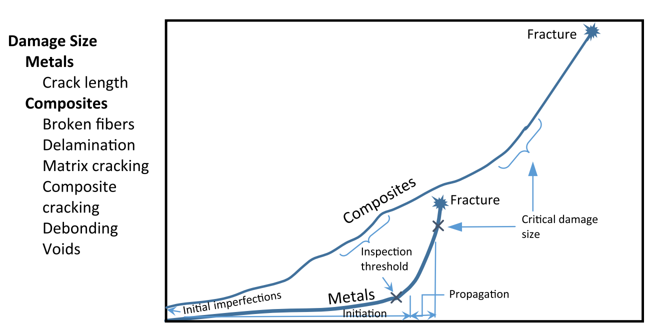

Fig. 6. Comparison of fatigue damage in metals and composites [76].

more damage-tolerant than metals, depending on the laminate orientation (unidirectional composites are subject to splitting) and loading conditions – each fiber is a separate load path and therefore it was believed that a composite material is highly redundant [76].

Early damage detection was always a desirable aim in order to avoid premature failures. Materials under cyclic loading dissipate energy in the form of heat due to hysteresis effects in the material. At locations of high stress levels, more heat is released than elsewhere, resulting in a local temperature rise in those areas. Several detection methods, such as acoustic emission, ultrasonics, X-ray radiography, were already in use. The scanning infrared camera was successfully used in [73] to visualize the surface-temperature field of steel and fiberglass-epoxy composite samples during fatigue tests. The information obtained in this manner allowed prediction of the probable location of the greatest fatigue damage well before such damage became visible in the form of a crack. Similar non-destructive damage detection techniques were introduced in [87,88] where the axial stiffness decrease and temperature rise were both attributed to irreversible damage in 45° GFRP and 45°/0°C/GFRP composites. The authors of [88] identify three stages in the composite damage progression process based however on the residual strength (in contrast to methods subsequently presented once again assigning three stages to the fatigue damage, based however on stiffness measurements, e.g. [89].

The effects of additional parameters that could affect the fatigue life of composite materials were investigated during this period, including temperature and water (moisture), especially for marine applications. Works on the effect of (salt) water in combination with the high pressure of great sea depths have been reported as early as the 1960s, see e.g. [90,91], with the first fatigue investigations reported immediately after 1965 [92,93]. Results showed that water may attack a polymer by plasticization, a reversible process, and by "corruption" of the polymer structure, an irreversible process, both of which affect the time-dependent response of the composite due to the degradation of the matrix by hydrolytic and other processes. Nevertheless, the information collected at that time was insufficient to reliably predict the engineering response of composite materials to water [93].

Alternative fatigue experimental studies were also reported concerning e.g. bending fatigue results at high temperatures, [94], a rotating cantilever fatigue test proposal [95]. During the same period, significant work was performed (for the aerospace industry) on full-scale structural testing to increase reliability. As reported in [76], the data obtained from small specimen tests must be reduced for reliability (typically three times the value of the standard deviation), surface finish, and size factor, and verified by full-scale testing before a design allowable is established. At that time there was a very limited amount of full-scale fatigue test data for composites, and reliable design allowables are therefore not readily available. The most substantial body of full-scale structural fatigue data concerned helicopter rotor blades [15,96] indicating that composite structures are highly fatigue-resistant in aerospace applications compared to metallic structures, and that joints and attachments remain a major design problem, especially in fatigue. Therefore, work on the fatigue of composite joints was initiated, see e.g. [97]. The potential for using fiberglass stabilizers for the T2A trainer aircraft was exploited by performing full-scale quasi-static, fatigue and vibration tests on GFRP structural components built with an external configuration similar to aircraft horizontal stabilizers [98]. The average structural efficiency of the GFRP stabilizers (strength-to-weight ratio) was similar to that of the metal stabilizers, although the GFRP components were stiffer in bending but more flexible in torsion. The reliability of GFRP (fatigue strength in [98]) was examined by the application of a spectrum loading (variable amplitude profile) and it was found to be superior to that of metal stabilizers. Similar conclusions were obtained for the feasibility of using GFRP in primary load-bearing aircraft structures such as wing box beams [99].

In parallel to the experimental investigations, a series of fatigue theories were developed aimed at predicting the fatigue performance of composite materials under different loading conditions. The most prominent fatigue failure theory of that time is probably the one proposed by Hashin and Rotem in 1973 [41]. Prior to this, in 1972, Broutman and Sahu [100] proposed a modified linear Miner's rule, based on a linear strength reduction of the specimen, that could more accurately predict the fatigue behavior of fiber-reinforced plastics. At the same time, Owen and Howe [101] presented a theory to predict cumulative damage in GFRP materials, dealing with multistage (block fatigue) loading and suggesting that a suitable cumulative fatigue damage law for composites should be non-linear and stress- independent. Those initial attempts at the development of fatigue theories for composites were supplemented by efforts that were more concentrated in the following time period, after 1975, as described in the next sections.

3. Mature composite fatigue investigations (1975–2000)

As stated by Lauraitis in the ASTM STP 723 preface, [102], already in 1981, "Composites had come of age. They had moved from the laboratory into the shop and were ready for their next step into service in critical structures - perhaps. With this last step imminent, durability and damage tolerance inevitably forced themselves into view. Therefore, our energies and efforts over the last years have been funneled into studying fatigue and environmental effects". Nevertheless, despite all these developments and the discovery of events and processes down to the microscale, the engineering community was still facing considerable uncertainties regarding methods to avoid fatigue failure when attempting to design a component or structure. Most of the investigations up until this time were focusing on the descriptive analysis of the observations at different scales without much success concerning the prediction of fatigue behavior. After 1975 the majority of publications related to the experimental investigation of composite fatigue behavior were more detailed, dealing with more specific subjects than works of previous years, and attempted to investigate the effect of several parameters on the fatigue performance of different families of composite laminates and joints, e.g. [14,103–107]. Fatigue was connected to fracture and creep, see e.g. [71,108–110], as had also been done previously for metals [111], when it was suggested that the "cyclic creep" phenomenon that appears in the upper portion of the composite S-N diagram (high stresses, low cycle fatigue) that can flatten out the curve to a "cyclic creep limit". This behavior was implicitly covered by the S-N type equations proposed by Sendeckyj [112] allowing, depending on the material and available quasi-static (residual strength) and fatigue data, the derivation of S-N curves that flatten towards the left-hand side. The method proposed by Sendeckyj in [112] suggests the following equation for the derivation of the S-N curve based on the assumption that the strength data (quasi-static, fatigue, and residual strength) follow a two-parameter Weibull distribution. The shape, α_f, and scale, β, parameters are estimated by Maximum likelihood estimators, while an optimization procedure should be followed to estimate the other two model parameters, namely C, and S. When the model is defined, the fatigue curve can be plotted for any desired reliability level $P_S(N)$ (including 50% ,which denotes the mean value of experimental data) by using the following equation:

$$\sigma_{\max} = \beta\left\{[-Ln(P_S(N))]^{\frac{1}{\alpha_f}}\right\}[(N-A)C]^{-S} \tag{1}$$

With $A = -\frac{1-C}{C}$. A typical S-N curve from this equation is presented in Fig. 7.

Sendeckyj's method therefore has a physical background, based on the wear-out model initially introduced by Halpin et al. [113] for composite materials based on metal crack growth concepts, and due to objections to the dominant crack assumption for composites, the method has been reviewed and modified by a number of authors considering residual strength as the damage metric. The form of the wear-out model adopted by Sendeckyj was based on the 'Strength Life Equal Rank Assumption' or SLERA, introduced by Hahn and Kim [114].

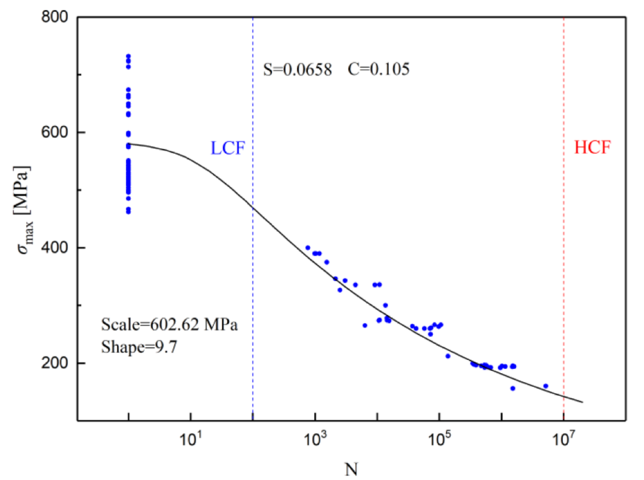

Fig. 7. Typical S-N curve for multidirectional glass epoxy material at $R = 0.1$ (MD2 R040 – $[(\pm 45/0)_4/\pm 45]_T$, [28]).

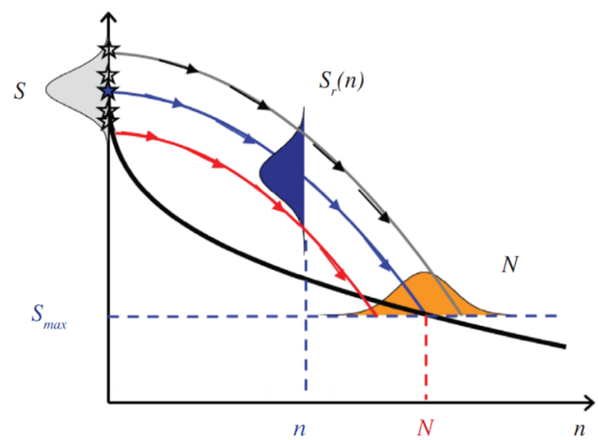

Fig. 8. Stress life equal rank assumption [115].

SLERA suggests that a specimen of a certain rank in the static strength probability distribution has the same rank in the fatigue life distribution – a schematic representation of the SLERA assumption is shown in Fig. 8. In other words, application of the wear-out model is valid as long as no competing failure modes are observed during fatigue life, or even between the fatigue and static loading.

Methods for the S-N curve modeling of composite materials, also appropriate for the derivation of S-N curves that take into account the probabilistic nature of the fatigue properties of composite materials, have been established to permit the derivation of S-N curves with a given statistical significance based on limited datasets e.g. [112,116]. These statistical methods, presented in detail in Vassilopoulos and Keller [4], are also based on a deterministic S-N equation for representation of the fatigue data; however a more complicated process, compared to the simple regression analysis, is followed for the estimation of model parameters, which in one of the presented models (wear-out) leads to a multi-slope S-N curve.

A review of articles on the fatigue behavior of composite materials shows that the fatigue failure mechanism can alter with changes in the cyclic stress level [117–121], explaining variation in the S-N curve slope. Different fatigue behavior was, for example, identified at high and low stress levels for an injection-molded polysulfone matrix composite reinforced by short glass and carbon fibers [117]. Experimental results showed a significant change in the S-N curves at around 10^3 to 10^5 cycles. Different fatigue responses under high and low stress levels were also reported in [118,120] for carbon/PEEK laminates where the dominant failure changes from fiber to matrix damage when the cyclic load level is decreased. Investigation of the fatigue behavior of glass/polyester $[0/(\pm 45)_2/0]_T$ composite laminates [121] showed a significant difference in the stiffness degradation at failure (it was found to be higher for lower stress levels), although no difference was identified in the fracture surfaces. Miyano et al. [119] reported different failure modes under low and high stress levels in conically-shaped FRP joint systems, proved by observation of the fracture surfaces and a lower slope of the S-N curve at high stress levels.

Fatigue damage was attributed to specific damage mechanisms that could, at that time and with the available equipment, be identified [122–124], although their effect on fatigue life could not yet be quantified. Nevertheless, by 1980, see e.g. [52], there was wide agreement that the fatigue damage propagation in laminated composites is controlled by the matrix, and that degradation of the laminae under fatigue loading first occurs in the matrix, while damage in the fibers is the result of the matrix degradation. According to [52] the limiting factor in fatigue is not the fiber but the interface or the matrix itself, as also discussed in [125,126]. The anisotropic nature of composites raised questions regarding the effect of the biaxial stress states that develop during loading, since even small off-axis stress components can be very critical [69,122–124,127–130]. Composite anisotropy also caused different mean stress effects than those in metals [131] with constant life diagrams shifting to the right [132,133], since composites are usually stronger in tension than in compression, as shown in Fig. 9, confirming what was initially stated by Boller in [16]. Similar work was performed for the investigation of the effect of the stress ratio, the ratio of the minimum over the maximum cyclic stress, $R = \sigma_{min}/\sigma_{max}$ [22,48,133–136].

The polymer matrix of composites makes them sensitive to frequency changes [137–147]. As a general rule, the test frequency should be chosen so as to minimize the hysteretic heating of the material. The source of this heating effect is hysteresis in the resin and the fiber matrix interface. Fiber-dominated laminates, such as unidirectional laminates loaded in the fiber direction, exhibit little hysteresis heating, and therefore frequencies up to 10 Hz, or even more, can be appropriate. Nevertheless, matrix- dominated laminates, those with fewer fibers in the loading direction, usually exhibit higher hysteretic heating, and as a guide, frequencies should be limited to 5 Hz, or less [137], depending however on the stress level, to avoid exceeding the glass transition temperature of the matrix and causing premature failure. Alternatively, different frequencies can be used to test the material at different stress levels, aiming to keep the loading rate constant as described in [138,139]. Research studies on the effect of frequency on fatigue lifetime support these arguments and prove that dependence of fatigue life on loading frequency is due to heating the material at higher frequencies, or creep fatigue at lower frequencies, or their interaction [140–145]. At lower frequencies, no temperature rise is encountered, however, more time is spent at maximum load, leading to creep effects and resulting in a decreased fatigue life, as mentioned for example in [135,140,142,143,146]. A tentative explanation of this phenomenon is schematically given in Fig. 10.

Another interesting aspect of this issue is reported by Perreux et al. in [142]. As the temperature rises due to energy dissipation, the life of each specimen depends on its geometrical shape and therefore its ability to dissipate heat. Thus, fatigue life may not be intrinsic to the material at higher frequencies, but a function of the shape and size of test specimen.

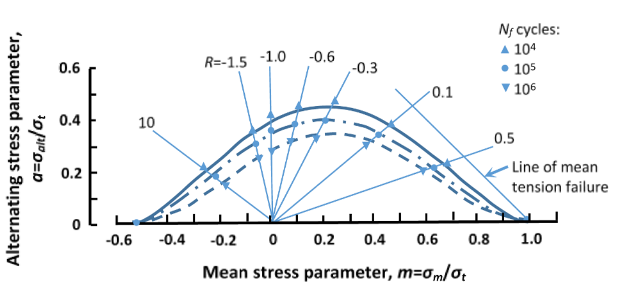

Fig. 9. Constant life diagram for $[(\pm 45, 0_2)_2]_S$ T800/5245 laminate [136].

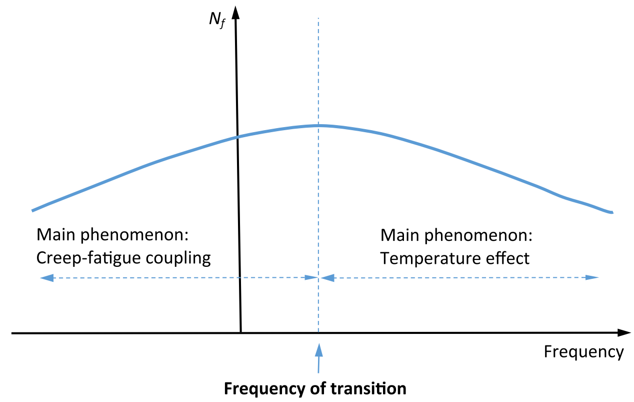

Fig. 10. Variation of lifetime according to frequency [146].

More experimental programs – investigating the effects of additional parameters such as specimen geometry, different material systems, environmental conditions, and different loading profiles – have been performed, e.g. [137,147–150]. Regarding the specimen geometry, as mentioned in [137], the main requirement is that the specimen should fail in a manner similar to the material of the comparable structural component. The literature on composite fatigue behavior contains many papers reporting work carried out on and comparing different specimen configurations for fatigue testing, in efforts to meet these requirements. Works on more complicated material systems, e.g. woven carbon and glass fiber composite laminates [151], appeared providing insight into the fatigue damage development in such cases, see e.g. Fig. 11. More complicated loading conditions were also implemented in the experimental campaigns [69,152–154] as it was realized that in-service loading is rarely of the constant amplitude variety and random loading has to be considered [7].

Work on the identification of fatigue damage mechanisms undertaken during the previous years was complemented in this period by the development of conceptual models, which, by simplification of the damage mechanisms and their interactions, attempted to attribute damage progress to the reduction of relevant properties, such as stiffness and strength. The objective was to explain/describe how damage reduces laminate strength and stiffness during long-term fatigue loading, and how damage combines to cause the fracture event that defines the life of a laminate [155]. Fundamental concepts concerning fatigue damage progression and lifetime assessment were introduced aiming to address the aforementioned objective, see e.g. [114,156–163]. Fong [156] introduced a conceptual definition of fatigue damage to assist the

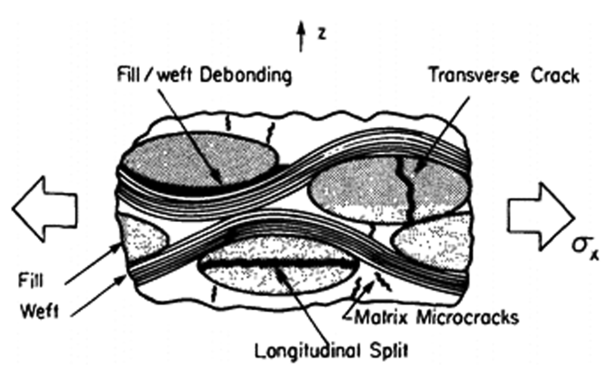

Fig. 11. Schematic illustration of damage in woven fabric composites loaded in tension [151].

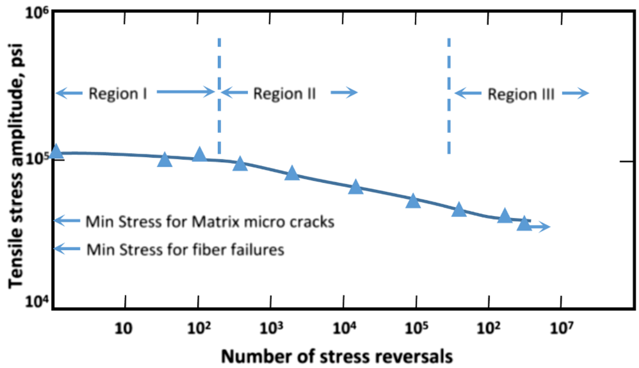

Fig. 12. S-N curve showing three different slopes assigned to three different damage mechanisms [158].

selection of measurement techniques and parameters for correlating damage with fatigue life. Fong probably introduced the term "damage parameter", a scalar quantity adopting values between 0 (damage free) and 1 (completely damaged) to define whether or not a material is close to failure. Damage development (in many cases crack formation) is different for different laminates [164], see for example the discussion in [160,163] for unidirectional and multidirectional laminates, or [151] for woven carbon and glass composites. Nevertheless, the developed theoretical approaches, either those of a phenomenological nature, or those involving some physical background, were able to model different material systems. Reifsnider [163] introduced the term "characteristic damage state" to describe the damage state that forms prior to fatigue failure, which is independent of the load history or specimen geometry, but depends on the laminate properties, including the stacking sequence.

Dharan [158] suggested that the fatigue response of the unidirectional GFRP he was investigating can be conveniently divided into three regions of interest corresponding to regions of markedly different slopes and assigned them to different damage mechanisms activated in each region, see Fig. 12. This interpretation was then adopted by Talreja [161] for the derivation of the so-called fatigue life diagram. Talreja [161] suggested that the fatigue life curve of any composite material would consist of different components, each corresponding to the underlying damage mechanism; based on this, he introduced the concept of the fatigue-life diagram shown in Fig. 13, by plotting the logarithm of the fatigue cycles against the applied maximum cyclic strain to facilitate interpretation of the fatigue mechanisms and their relative roles. Both fibers and matrix are subjected to the same strain during fatigue and therefore strain was chosen instead of stress for the fatigue-life diagram derivation. The proportion of each region in the fatigue-life diagram varies depending on the material as shown explicitly in [161]. Although oversimplified, this interpretation provides an overall impression of the failure mechanisms for each examined material.

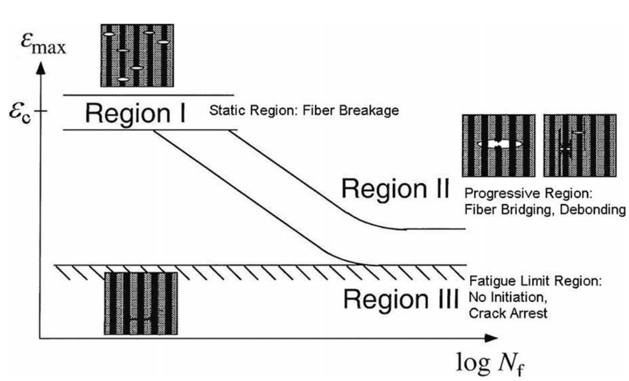

Fig. 13. Fatigue life diagram according to Talreja (From [165]).

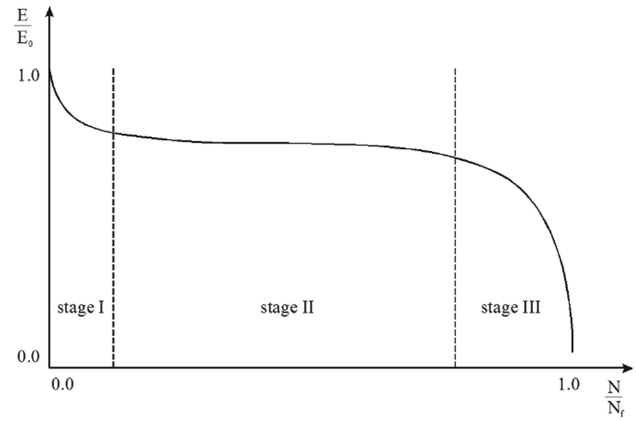

Fig. 14. Typical stiffness degradation for composite materials [90].

Similar behavior was observed in fatigue stiffness measurements with early investigations on the topic conducted by the research groups of Schulte [166–168], and Reifsnider [169,170], summarizing their research on the graph presented in Fig. 14, also indicating three stages related to different damage mechanisms as described in [90].

Fatigue damage also affects the residual strength of the material. Chou and Croman [157] introduced the term "sudden death" to characterize the sudden failure of a material when the residual strength drops (due to the accumulated damage) to the developed fatigue stress. In contrast to the strength degradation models [114], which assume that the strength of each specimen decreases slightly after each fatigue cycle, the sudden-death model assumes no degradation for individual specimens up until very close to failure. As shown in [157] the sudden-death model describes the data for unidirectional materials better than the degradation model, but the degradation model is better than the sudden-death model for composites that contain a substantial percentage of off-axis plies. A schematic representation of typical strength degradation behaviors for composites is shown in Fig. 15.

It was mainly during the decade 1990–2000 when the first reviews on the subject appeared in the literature summarizing the available knowledge, either regarding experimental investigations, or theoretical approaches for modeling the behavior and predicting the fatigue life of composites [172–177]. Henceforth, experimental investigations and modeling approaches were developed in parallel and it is not surprising that most of publications of that period included especially designed experimental programs to establish and validate the introduced theories, see e.g. [41,63,101,127,179–187].

According to Sendeckyj [178], theoretical models can be classified

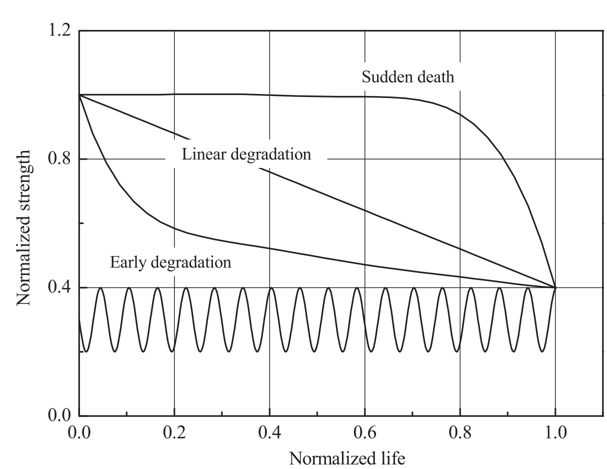

Fig. 15. Schematic representation of typical strength degradation behaviors for composites [171].

into two major categories. The first consists of theories based on macroscopic failure criteria and theoretical formulations to predict life under constant or variable amplitude loading. Theories in this category do not take into account the experimental observation of the damage mechanisms and their development during fatigue loading. Theories in the second group are all based on actual damage measurements during fatigue life. Thus, a damage metric is used as an indicator of damage accumulation. According to the damage metric, these theories can be further classified into sub-categories: strength degradation fatigue theories, where the damage metric is the residual strength after a cyclic program and stiffness degradation fatigue theories, where stiffness is conceived as the fatigue damage metric, and finally, actual damage mechanism fatigue theories based on the modeling of intrinsic defects in the matrix of the composite material that can be treated as matrix cracks. Theories of this group are known as "physical-based theories" and are presumably not of a phenomenological nature.

Scientists and engineers puzzled for decades over the problem of finding the best theory to simulate/predict the fatigue behavior of several composite material systems and quantify the effect of damage (of any type) on fatigue life. The ideal fatigue theory is described in [178] as that based on a damage metric that accurately models the experimentally observed damage accumulation process, takes into account all pertinent material, test and environmental variables, correlates the data for a large class of materials, permits the accurate prediction of laminate fatigue behavior from lamina fatigue data, is readily extendable to two-stage and spectrum fatigue loading and takes into account data scatter. These requirements cannot be met simultaneously for many reasons and theoretical models that address only some of them have been introduced and accepted by the engineering and scientific communities. In practice, even theories of the second category (the so-called "physical based theories") are mainly of a phenomenological nature. Moreover, several theoretical models that have been suggested as predictive methodologies can eventually be used only for modeling/simulation since they contain circular arguments (argument in which the evidence for a proposition contains the proposition itself [188]) in their formulations.

4. Later composite fatigue investigations (2000–2020)

Despite efforts made during previous decades, there is still no commonly accepted fatigue life prediction methodology that could satisfy the requirements stipulated by Sendeckyj in [178]. The abundance of material systems, the multitude of environmental and loading conditions and exhibited damage modes and their interaction make it impossible to follow one approach or another. Nevertheless, this challenging variation of parameters affecting the fatigue life of composite materials opens up new research directions as discussed in this section.

Developments in inspection techniques over the last 20 years have allowed researchers to validate previously introduced methods, such as infrared inspection to monitor damage evolution and thermal behavior of composites during fatigue loading, as shown in Fig. 16 [29–31,73,187,189,190]. New monitoring methods were also introduced, such as optical fiber methods, e.g. Fiber Bragg Grating (FBG) sensors that were successfully used for the strain development and temperature measurements during the fatigue of thermoplastic polymer composites in [191].

More traditional non-destructive inspection methods, such as acoustic emission, have also been implemented for the life assessment and structural health monitoring of composite materials and structural components [192,193]. Scanning electron microscopes, e.g. [194] and X-ray computed tomography can also be used for in-situ and ex-situ damage measurements in composite materials [195]. X-ray tomography is very promising for the identification of damage in composite materials, although not without disadvantages, especially when the in-situ investigation of laminates in fatigue is involved. Tomography is nevertheless very good for large scales, when for example the damage under investigation is an interlaminar crack running into a laminate, see e.g. Fig. 17, at least with the existing technology. It is questionable whether or not an analysis can be performed at lower scales, to identify fiber/matrix interface damage for example or matrix damage as presented in [195–197] since only small volumes can be scanned to obtain good resolution at this scale. Other, optical methods, such as digital image correlation (DIC) have proved appropriate for the inspection of damage in composite materials both in quasi-static and fatigue loading. Examples are given in e.g. [10,198] that investigate the kink behavior of non-slender glass fiber-reinforced epoxy prismatic specimens, and e.g. [199] that compares the efficiency of X-ray tomography, DIC and acoustic emission for the fatigue damage monitoring of thick composite laminates in bending.

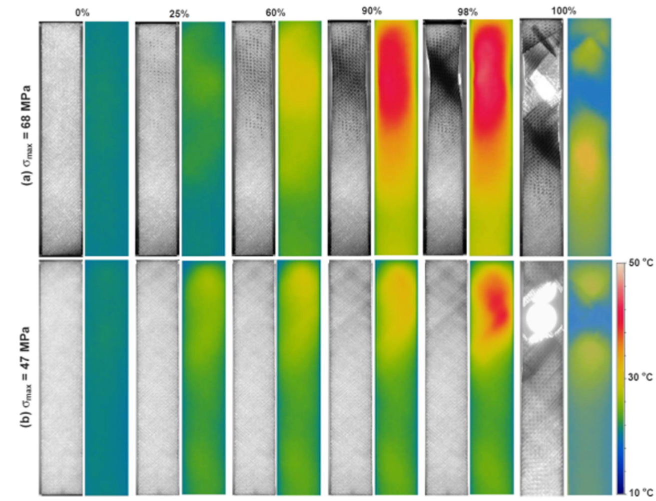

Fig. 16. Light transmittance (damage indicator) and self-generated temperature at different percentages of fatigue life at two stress levels [29].

These monitoring/inspection methods allowed the identification of damage modes and damage development during cyclic loading, see, e.g. [29–31,200–205]. They have also been implemented in studies regarding material and specimen geometry selection, see for example [206], where finite element modeling was combined with full surface field temperature measurements by a digital camera and an infrared camera to investigate the effect of specimen geometry and different fabric reinforcements on material fatigue life. Damage monitoring methods have also proved valuable for the identification of testing artifacts (effects of the experimental set-up on the obtained results), see [207–211].

During this latest period, scientist have also attempted to revisit old problems, and scrutinize previous works, by performing a "meta research" analysis to clarify issues overlooked in the past. Additional studies were made to complement existing ones from previous periods regarding loading effects, both on composite laminates and adhesively-bonded composite joints, including, but not limited to, the sequence effects [212–216], frequency effects [217–219], creep/fatigue interaction [30–32,49,115,220–226], and *R*-ratio effects [25,34,68,121,193,230–232], especially those resulting in compression fatigue. Additional efforts were devoted to biaxial/multiaxial loading [233–238], or spectrum/variable amplitude loading [4727, 215, 240] experimental campaigns, to complement other existing works attempting to approach realistic conditions as far as possible.

Today it is commonly accepted that frequency (and therefore loading rate) affects the fatigue behavior of composite laminates due to the viscoelastic nature of the polymeric matrices. Mixing quasi-static data with fatigue data is questionable, especially when the quasi-static data are derived at different (usually much lower) loading rates than the fatigue data. High frequencies can be beneficial, as long as they do not create hysteresis heating that can raise the material temperature up

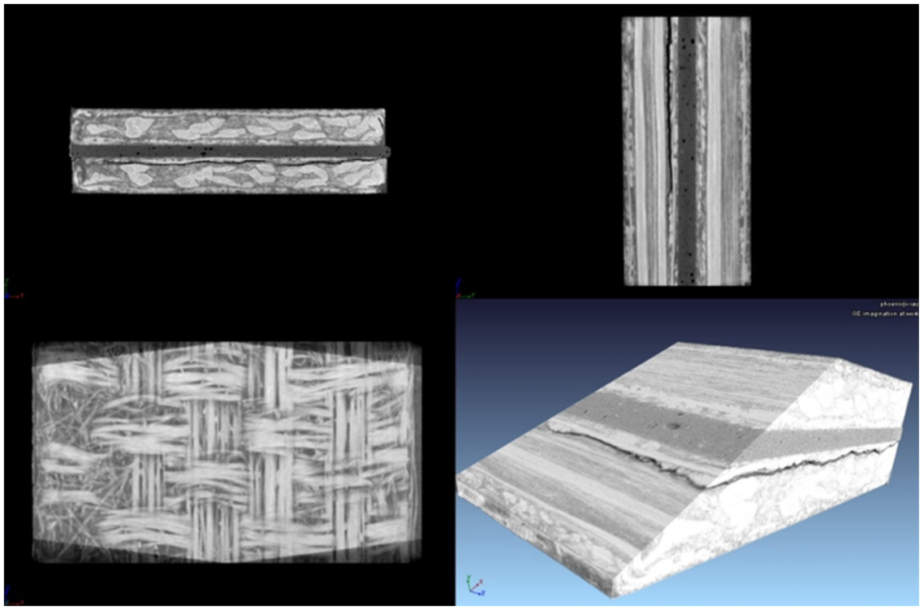

Fig. 17. X-ray tomography of adhesively-bonded connection (GFRP pultruded adherends, paste epoxy adhesive) – (Courtesy CClab/EPFL).

to the matrix glass transition temperature and make the material more susceptible to creep. Investigation of the combined creep-fatigue behavior of composite structures can be performed either by segregating the creep and fatigue elements of loading and adding their effects (in a linear on non-linear way) or by assuming both effects simultaneously by subjecting the component to a loading profile with a measurable time under load [227]. The second is a more realistic scenario for the description of "creep-fatigue loading", while "pure creep" or "pure fatigue" loading are considered as special cases [228,229]. There is little information in the literature regarding the effect of creep on the fatigue life of composites because of the complexity of such effects and the difficulty to clearly separate the two phenomena. The results obtained show that creep and fatigue are mutually influencing phenomena, with some studies demonstrating a beneficial effect of creep on fatigue life, e.g. [31,32,52,109], while others show that creep can act synergistically with fatigue mechanisms to accelerate damage accumulation [14,227]. However, it is commonly accepted that to a great extent, creep plays a significant role for the high cycle fatigue regimes, especially at low frequencies, when the time under load is increased [31,32,72,240]. In such cases time-dependent failure occurs, while the failure is mainly cycle-dominated at low cycle fatigue regimes [14,224,226]. The physics of damage are different for cyclic fatigue and creep since these are mechanisms that involve different types of damage processes [241]. Experimental evidence concerning composite failures of glass fiber-reinforced polymers shows that cyclic loading causes mainly stiffness degradation, and does not affect their viscoelastic response, which is a creep-related mechanism [242].

The stress ratio (R-ratio) affects the fatigue performance of composite laminates. Experimental evidence supports the argument that the slope of the S-N curve, characterizing the behavior of a composite material, is a function of the stress ratio. For the same loading type, either T-T, or C-C, there is a consistent trend suggesting steeper S-N curve slopes for lower R-ratios as shown for characteristic material systems in Table 1. Although different models exist for the simulation of the fatigue life of composite materials, adhesives and joints, as described for instance in [60], a typical power law S-N equation was implemented here for modeling the fatigue stress vs. life behavior of the examined materials:

$$\sigma_{\max} = \sigma_o N^b \tag{2}$$

in which N denotes the number of cycles to failure, $\sigma_{\max}$ corresponds to the maximum cyclic stress, while σ_o, b are the fatigue model parameters, derived by linear regression analysis of the experimental fatigue data.

Table 1
S-N model parameters for composite material systems.

	Material designation	R	σ_o (MPa)	b	Ref.
P2BT-T	Glass & carbon/epoxy $[\pm 45/90_4]$	0.10 0.50 0.70	87.2 91.4 83.7	−0.060 −0.046 −0.026	[27]
DD16-C	E-glass/polyester $[90/0/\pm 45/0]_S$	10.0 1.43 1.10	480.7 437.2 490.7	−0.068 −0.021 −0.020	[27]
UT500/135-T	Twill-woven UT500 carbon fiber and 135 epoxy	0.05 0.50 1.00	782.2 676.6 649.0	−0.074 −0.036 −0.027	[244]
DLJ-T	Pultruded GFRP bonded double-lap joint	0.10 0.50 0.90	38.5 43.1 31.7	−0.083 −0.075 −0.031	[245]
T800S-25 °C-T	Carbon/epoxy $[(45,-45)/(0,90)]_S$	0.05 0.50 1.00	1285.1 1134.6 994.1	−0.051 −0.030 −0.018	[244]
DD16-T	E-glass/polyester $[90/0/\pm 45/0]_S$	0.10 0.50 0.90	732.8 814.6 688.2	−0.102 −0.094 −0.045	[27]
DLJ-C	Pultruded GFRP bonded double-lap joint	10.0 2.00 1.10	32.5 30.3 30.3	−0.043 −0.032 −0.016	[245]
T800S-170 °C-T	Carbon/epoxy $[(45,-45)/(0,90)]_S$	0.05 0.50 1.00	757.5 690.6 709.7	−0.093 −0.065 −0.058	[244]
QQ1T-T	E-glass/epoxy $[\pm 45/0_2]_T$	0.10 0.50 0.70	147.6 156.9 144.5	−0.082 −0.073 −0.050	[27]
T400/3601-T	Satin-woven CFRP laminates	0.10 0.50 0.80	1033.8 1026.8 1048	−0.040 −0.025 −0.019	[243]

Compression-compression or tension-compression fatigue loading is very inconvenient for researchers since the compressive components can cause buckling of the usually slender composite specimens. Several solutions were proposed for addressing the problems that arise during

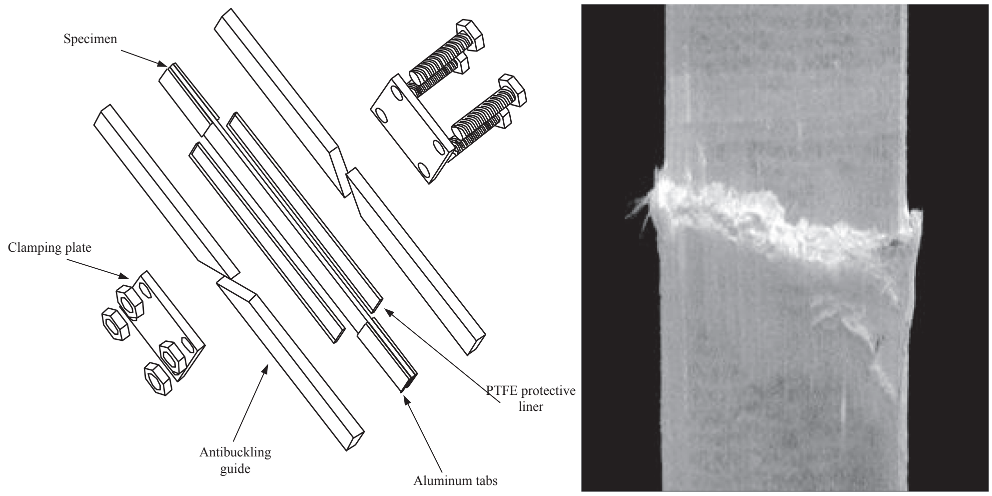

Fig. 18. Antibuckling device for compression fatigue of composite laminates, and typical fatigue failure of specimens at σ_a = 70 MPa, R = 10 [4,251].

fatigue loading under compression, probably the most contentious type of testing for composites [246]. Early works can be traced back to the mature period comparing antibuckling solutions [247] and suggesting the use of supported test fixtures, such as the Celanese fixture and the IITRI test fixture [248], adopted later in ASTM D3410 [249], or the Boeing fixture defined by ASTM D695 [250], which recommended a supporting jig for thick specimens. Several other antibuckling support techniques have been proposed, see for example the fixture shown in Fig. 18 used for supporting the slender (ASTM standard) specimens of multidirectional laminates under compression [251], but all have produced contradicting results [246].

To alleviate the buckling problem in compression under quasi-static loading, ASTM3410 [249] suggests a short, thick specimen. This same configuration has been implemented in [252,253] for the compression-compression fatigue investigation of unidirectional and multi-directional composite laminates for wind turbine rotor blades. A short specimen with a characteristic compressive failure mode is shown in Fig. 19. The complete data set is publicly available via the Optidat database [28].

A similar approach has also been followed by other authors [253], investigating the fatigue behavior of CFRP laminates, by testing specimens with 100-mm free length in T-T fatigue, and specimens with a smaller free length of 10 mm in T-C fatigue loading.

Bending fatigue experiments have also been performed for similar reasons (to avoid buckling from compression) but also for the simplicity of the supporting equipment as well as to avoid unexpected and unwanted failures at the load transfer areas (gripping areas). The ASTM D5467/ D5467M [255] standard recommends transmitting compression loads by subjecting a honeycomb core sandwich beam with thin skins to four-point bending, limited however to prepregs with unidirectional fibers. Additional works have been published on the bending fatigue of several composite material systems, e.g. [256–263], suggesting that this type of loading has advantages compared to the "traditional" tension and compression loading, basically the simplicity of the specimen geometry and the loading conditions, but also the potential for obtaining more information from one specimen regarding fatigue damage as the stresses and strain can vary along the gauge

Fig. 19. Short laminate for compressive fatigue – Typical UD compressive failure at R = 10 [253].

length [259]. Nevertheless, bending fatigue has disadvantages, such as the difficulty of bending specimens until failure due to the large deformations necessary [264].

Although most of the presented works deal with the usual types of composite materials, i.e., carbon, glass fibers, epoxy, vinyl ester, polyester resins, and thermoplastic composites, significant research efforts have been undertaken, especially during the last 20 years, for investigation of the performance of other material systems. Basalt fiber composites [265–268], bio-composites [269–275], as well as hybrid composite systems [40,262,276–279], have been introduced and their performance has been investigated, with an eye to their potential contribution to sustainable development. This can be achieved for example by using inexpensive fibers as raw materials. These mineral amorphous fibers are a valid alternative to carbon fibers thanks to their lower cost, and to glass fibers thanks to their strength [266]. Damage-tolerant design approaches for extended operational lifetime are possible when using hybrid composites [176]. With this same purpose, self-healing composites [280–283] and their fatigue performance were examined and it was proved that implementation of a kind of self-healing functionality in fiber-reinforced polymer composites can extend their fatigue life, see e.g. [228]. Thermoplastics are also advantageous candidates for sustainable designs with their good recyclability potential. The investigation of their fatigue behavior had been the subject of several works in the past, but also in the last period, see e.g. [33,211,284–288]. Apparently, the introduction of such a broad range of new types of composite materials calls for additional efforts for confirmation of the material behavior under conditions that have already been thoroughly investigated, including effects that have been discussed in the previous paragraphs.

Lately, research was also devoted to the investigation of the fatigue performance of new material system designs, such as thick laminates, e.g. [37–39,199,289,290] and thin-ply laminates [40,291], or 3D additive manufacturing in emerging applications for composite materials [292–296]. Thick composite laminates can be found in different wind turbine blade sections, such as the root or spar caps. For 40-meter-long blades, thicknesses between 30 and 50 mm are typical. Root and cap thicknesses between 100 and 150 mm can be considered common for 60 to 70 m-long blades. [297]. Thick composite materials may have an increased likelihood of multiple flaws being grouped in the same local area or of larger areas of porosity. However, there may also be offsetting improvements due to larger size, such as the likely arrest of damage as it spreads from local stress concentration areas, which does not occur in test specimens due to their small size and cut edges [298]. Ultra-thin-ply composites are becoming commercially available and are increasingly used in high-end applications. Reducing the ply thickness can lead to dramatic improvements in terms of first-ply/first-damage criteria, but also in terms of fatigue life and ultimate strength as was shown in [40]. These significant improvements have been attributed to a change in the failure mode: thin-ply composites exhibited significantly delayed damage growth and a quasi-brittle failure instead of extensive delamination and transverse cracking patterns in [40]. The implementation of composites in newly developed applications, such as offshore wind energy, necessitated additional research efforts in this direction. Little has been done to date though, see for example [299] where methodologies for the fatigue assessment of off-shore wind turbines have been derived, or the fatigue performance of polyamide mooring ropes was investigated [300], together with research investigating the combined effects of water immersion and temperature on the fatigue behavior of composites, such as [301].

The manufacturing of thick, thin, 2D printed and other types of composites can create production-induced defects. The effect of such defects, but also of defects that appear during the service life of composite structural components is, occasionally, essential for their quasi-static and fatigue performance. Investigations of the effects of defects on the fatigue behavior of several composite material systems have been performed, e.g. [205,302–304], proving that both loading cases must be separately examined and analysed since a specific effect, e.g. delamination, does not significantly affect the static strength, but does however affect (more than 40%) the fatigue strength, as was presented in [302] for a GFRP system. Not many publications exist on the size effects of the fatigue of composites, with few examples discussing and modeling size effects in thin-ply composite laminates, e.g. [40], and it is assumed that in fatigue the same size effects as those extensively described in [305] can be expected.

The characteristics of the ideal theory for the modeling and, eventually the prediction of composite fatigue behavior were prescribed already in the 90 s, - see [178] and the relevant discussion in the previous section. Nevertheless, the scientific community has still not reached any agreement on the most appropriate failure criterion that should be met. Although numerous models have been introduced, especially in this later period, and validated by using existing, or specifically developed databases, a universal fatigue model able to provide predictions for a wide range of composite material fatigue problems does not exist.

Modeling has shown very early in this period that for the accurate fatigue assessment of composites, especially thin-walled box beam structures like wind turbine rotor blades, it is vital to take into account all stress components and not neglect the transverse normal and shear stresses, as was the case until ca. 2000. As shown in [63], see Fig. 20, fatigue calculations not taking into account the entire stress tensor can significantly overestimate fatigue life, leading to erroneous results and overestimating the bearing capacity of the multilayer composite.

A significant number of fatigue theories, mainly phenomenological models, were introduced during this last period, after 2000. These include simulation (descriptive), as well as predictive models, e.g. for S-N curve simulation [47,60,245,306], description of the CLD type [307–312], crack initiation [313,314], stiffness degradation [89,121,315–317], residual strength [318,319], prediction of fatigue life under variable amplitude spectra [26,69,70,239,320], off-axis fatigue behavior, e.g. [321–323], evolution of the hysteresis area, e.g. [324–326], and modeling of multiaxial fatigue damage in composites, e.g. [233–238]. Models have also been formulated for the progressive damage modeling of composite materials and structures, e.g. [70,209,327,328]. Fatigue damage theories have been implemented into computer software frameworks to provide tools for virtual testing, see e.g. [254,329].

Most of the models are empirical in nature [220], and require the use of different amounts and types of experimental data for their implementation [330], while in many cases their applicability is limited to certain materials. Nevertheless, phenomenological/empirical models have the ability to generalize predictions. If their parameters are

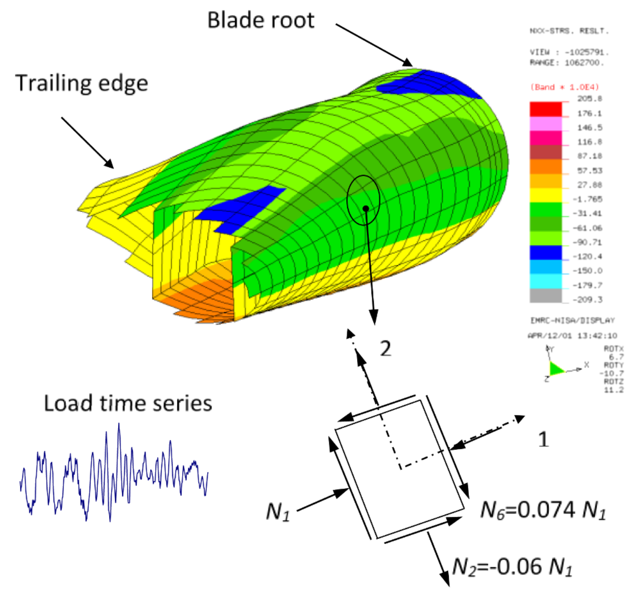

Fig. 20. Detail from GRP rotor blade root. Typical state of in-plane stress resultants [63].

appropriately calibrated with available data for each material system, they can simulate sufficiently accurately the fatigue behavior of a wide range of composites. Nevertheless, in order to keep the complexity of such models within reasonable limits, and maintain the amount of necessary data at a reasonable level, several effects on fatigue life estimations are deliberately omitted.

Most of the introduced models are usually capable of providing accurate fatigue predictions (limited mainly by their empirical character). However, for extrapolations to different scales (e.g. from the fiber/matrix characterization to the lamina fatigue prediction, from the laminate to the laminate, or from the laminate to the structural component) multi-scale modeling approaches should be adopted, such as those described in a series of articles in the special issue AFRL II, [331] and schematically shown in Fig. 21. In this exercise, the predictive ability of seven of the existing commercial/research progressive damage analysis (PDA) codes was evaluated, using available experimental data from open-hole specimens with three different stacking sequences in order to benchmark the ability of the seven analysis methods to predict property degradation due to fatigue loading [332]. The evaluated codes are actually hybrid models, combining phenomenological with physical-based theories to bridge the gap between scales and provide tools for virtual testing of structural components by using fatigue data at lower scales (effectively at the material level). Although these codes, as well as other similar works, were presented very early in this last period, their predictive ability is still very limited as was clarified in [333] and it seems that the day when accurate and credible virtual tools for fatigue will be available has not yet arrived.

During the last two decades, artificial intelligence methods, such as artificial neural networks, genetic programming, neuro-fuzzy inference systems etc. [61,62,334–347] have been employed, in order to, among other applications, assist the fatigue life modeling of composite materials. Thanks to these publications it has been proved that AI methods are capable of providing accurate simulations, e.g. of the S-N curve behavior as seen in Fig. 22, or for the derivation of CLDs, as seen in Fig. 23, when an appropriate set of experimental data exist. The use of AI methods in fatigue life modeling actually resembles a stochastic fitting procedure. The performance of the AI method depends on the input data used for its training. Therefore, when appropriate input data exist, the AI method can provide accurate fitting results, similar to, and occasionally better than, those given by traditional equations, as explicitly shown in Fig. 22. In Fig. 22(b) it is shown that the GP curve

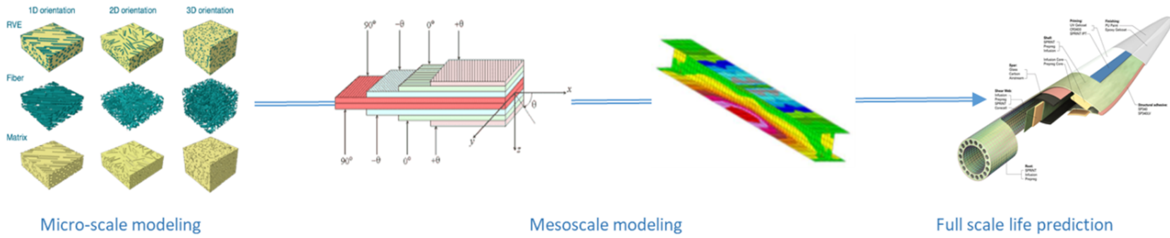

Fig. 21. Multiscale modeling approach linking the micro scale to the full-scale modeling of engineering structures.

"follows" the trend of the experimental data more effectively than the other three fatigue models that produce a somewhat straight curve on the Log(N)–S plane. For example, when examining the stress level of 80 MPa, the experimental average number of cycles could be calculated as 77,985 and the corresponding estimated numbers from the GP curve and other methods as 63,095 and 107,152 cycles, respectively [337].

The same good results obtained by the application of an artificial neural network for the derivation of CLDs for a multidirectional composite laminate are presented in Fig. 23. The drawback of the AI methods used in this way is that they do not provide any equation at the end of the procedure; they are used as "black boxes" fed by data to provide data. Therefore, although AI methods provide a stochastic output, this cannot be used in further fatigue analyses (e.g. in a life prediction methodology such as the one presented in [329]). This feature also causes another major unresolved problem of the artificial neural networks; their weakness in extrapolating model predictions outside the training set region.

Artificial neural networks were also used in combination with non-destructive monitoring techniques, e.g. acoustic emission for assessment of the remaining useful life of composites [348], as well as for the detection of structural damage [349]. Such "machine learning" tools together with data mining techniques, e.g. [350] are becoming effective in describing material behavior and analyzing the effect of several parameters that influence fatigue damage evolution.

5. Conclusions

The fatigue of composite materials has intrigued the scientific and engineering communities for the last 75 years or so, since the introduction of these "advanced" structural materials in several engineering applications. Very early in this period it was realized that the basic principles of fatigue as an engineering phenomenon are applicable to all materials and structures. Materials get tired; they wear out because loads are repeated again and again under changing conditions; superimposed loads, temperature gradients, stress concentrations, and environments [16]. This argument has been confirmed by the extensive experimental fatigue datasets that have been compiled for different composite material systems.

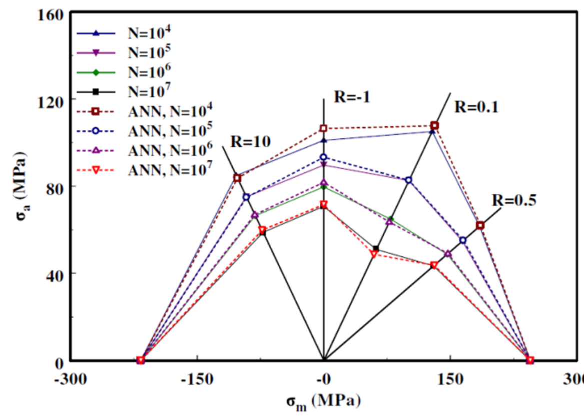

Fig. 23. CLD for [0/ ± (45)2/0]T laminates. Artificial neural network predictions vs. experimental data in the range 104–107 loading cycles [61].

During the early composite fatigue investigations, say between 1950 and 1975, basic experimental programs were established in order to understand the basic mechanisms leading composite materials to failure under fatigue loading profiles. In parallel, a few fatigue theories for the life modeling and prediction of composite materials were established and validated against experimental data sets derived especially for this reason, see e.g. [41,101]. Composites are used in a wide range of applications, certainly not only in aerospace and automotive where light weight is essential. Fatigue is an issue in all these applications.

During the "mature" period of composite fatigue investigations, say between 1975 and 2000, several experimental fatigue databases were derived and numerous theories developed aimed at the accurate modeling of the behavior and prediction of the performance of composite laminates under new loading conditions, off-axis angles etc. It was soon realized that multiaxial stress states, that develop in composites even under uniaxial loading, should be considered in fatigue life calculations.

Today, almost all fatigue failure mechanisms are recognized and their effects on fatigue life and damage evolution are quantified. An abundance of scientific publications and experimental reports have been published – much more than those cited in this article, together

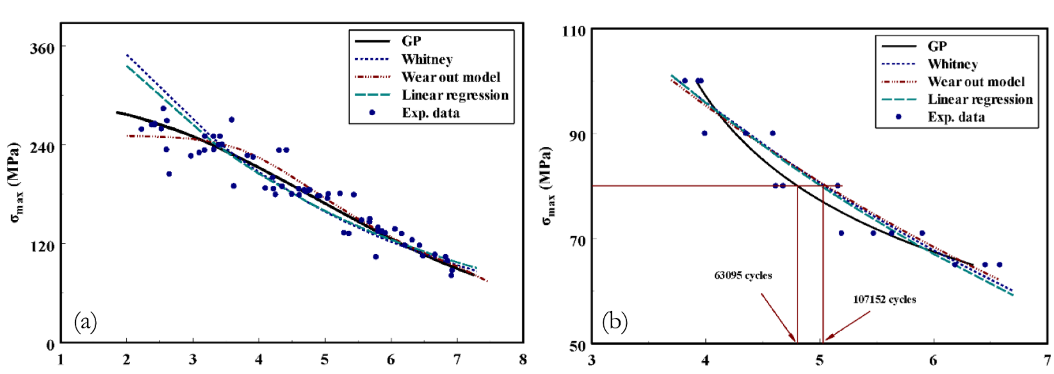

Fig. 22. Comparison of S-N simulations from genetic programming (GP) and other traditional modeling techniques for different materials [337].

with a series of review articles discussing different aspects of the fatigue behavior of composite materials, such as [42,131,172,174–177,351–356]. The various problems that can arise due to the multitude of testing parameters have been revisited in recent years to reduce testing artifacts and obtain credible experimental results. Nevertheless, there are still ambiguities regarding the combined effects of several parameters, such as the creep-fatigue interaction, mechanical and environmental loading combinations, etc. that cannot be overlooked, especially when designing composite structural elements for demanding applications, such as aerospace components or on- and off-shore wind turbine blades.

It has been explicitly shown that the synergistic effects of load, environment, geometry, residual strength, time, and material microstructure should not be overlooked. A large number of fatigue life modeling/prediction theories have been introduced. Most of these fatigue theories are empirical; their implementation is strongly based on fatigue data. The behavior is simulated and empirical models are occasionally used for the prediction of the same material behavior under different loading conditions, see e.g. [26,69,154,239] presenting theories for the prediction of the variable amplitude fatigue behavior of composite laminates based on data from their constant amplitude fatigue performance, or [41,43,63,72] that present theories for the prediction of the off-axis and multiaxial fatigue behavior of composite laminates based on uniaxial fatigue data.

Several of the theories that claim **not** to be empirical, are actually also empirical, for example fracture mechanics methods for delamination based on the measurement of the crack length are also empirical, since the final models are actually fitting equations that simulate the material behavior without having any physical meaning, and moreover, without modeling damage but rather the effects of it.

The high demand for experimental evidence to support the development of data-based fatigue life modeling/prediction methodologies resulted in a significant amount of experimental data. Nevertheless, this urge to obtain experimental data led in some cases to questionable databases, if not to completely erroneous results as explicitly discussed in [54]. It is also to be expected that, of all those theories presented in the literature, some should not be as effective as they have been claimed to be (see corollary #4 from [54]). The greater the flexibility in designs, definitions and analytical models in a scientific field, the less likely the research findings are to be true. Flexibility increases the potential to transform negative results into positive results i.e. bias that can falsify results. This is less possible in fields that use commonly agreed methods, e.g. S-N curves may yield a larger proportion of true findings, but becomes more possible in fields where analytical methods are still under experimentation, e.g. artificial intelligence, and where only "best" results are reported. This is another reason for additional research, and eventually the derivation of codes and standards, in such fields in order to reach common understanding and agreement. Even today, numerous scientific publications in the field are very superficial, resembling experimental reports rather than scientific papers seeking new knowledge and explanations for the observed phenomena. Part of the responsibility lies with the research set-up and the objectives set by each study – the correct questions need to be asked to get correct answers.

Technology advances provide the scientific community with amazing tools, allowing the design and execution of excellent experimental campaigns aimed at the detailed investigation of the fatigue behavior of composite materials. Computer science supports these developments via the implementation of artificial intelligence, machine learning, and data mining techniques, that have been proved very efficient in other domains to deal with complex multiparametric optimization problems, in engineering. The future of the topic looks prosperous, although very challenging. Several problems have been solved, whilst others still await commonly accepted, credible, solutions. Within the next few years the scientific community is expected to come up with reliable methodologies for the life prediction of FRP engineering structures, allowing rapid and reliable prototyping without the need for the fabrication and testing of numerous physical prototypes. In order to address the numerous developments that lie ahead, dedicated knowledge is required, spanning from basic fundamental science to pioneering technologies, across multiple disciplines. Implementation of the acquired knowledge will allow the development of a universal fatigue failure theory that can bridge the scales from the material to the structural level and will allow the derivation of virtual fatigue modeling tools in the near future.

This work mainly focuses on fatigue investigations regarding composite laminates and polymer materials and does not refer in detail to the relevant works for adhesively-bonded composite joints, composite sandwich panels, or fracture mechanics fatigue investigations. It serves as a historical review aiming to present developments since the beginning of the investigations of composite material fatigue behavior and does not comprise an extensive list of publications on any specific topic.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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