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DOI : 10.12762/2015.AL09-06

Fatigue Damage Modeling of Composite Structures: the ONERA Viewpoint

The aim of this paper is to present the fatigue damage modeling approach developed at ONERA for the fatigue life prediction of composite materials and structures. This paper is divided into five sections. The first one explains why the already developed and validated methods for fatigue life modeling of metals and alloys cannot be directly applied to composite materials. Thus, the proposal of an efficient fatigue model for composite materials necessitates a good understanding of the specific damage mechanisms that occur under static and fatigue loadings of composites. These damage mechanisms are detailed in the second section. Then, the next section presents the different types of models reported in the literature; among them, the progressive damage models, to which special attention will be paid. Finally, structural simulations and constant-life diagrams will be considered in the last sections.

Introduction

The introduction of composite materials in a wide range of structural components requires engineers and research scientists to reconsider fatigue loading as a factor inducing failure, even for structures where fatigue was not traditionally considered as an issue. Up to now, composite materials were considered as fatigue insensitive and one of the ideas implied behind this statement was that the conventional loading levels applied to components were far too low to initiate any local damage that could induce catastrophic failure under repeated loading. Then, the requirement for no growth of defects, i.e., manufacturing defects and accidental damage, has always been assumed to be sufficient for the design of composite airframes subjected to fatigue loading. However, this assertion has been questioned by the aerospace industrial sector. Indeed, with the continuous improvement of composite design methods during the last decades and the imperative of structural mass minimization for recent airliners, during in-life service composite structures are subjected to loadings increasingly closer to their static strength. To be more specific, increasing the operational loads in the structures by reducing the static strength margins down to their minimum values does not make fatigue critical for composite structures [68]. However, this assumption is likely to lead to situations where more unstable fatigue cracks develop in areas where out-of-plane stresses may be found. Fatigue is also inherently an important issue in rotating composite structures. Applications are as diverse as rotor blades for wind turbines and helicopters, marine propellers, flywheels, paper machine rolls, etc. Matrix fatigue degradation and fiber failure are the main failure modes and they should be avoided through sensitive design. An iterative process for the definition of different prototypes is usually required and, in order to reduce cost and time for product development, accurate fatigue behavior simulation is critical for composite structural components or structures.

Consequently, fatigue of composite structures is of growing interest and leads industrials to develop accurate fatigue modeling, as well as a better prediction of delamination in laminates during fatigue loading. Since fatigue of metallic materials is a well-known phenomenon, first attempts to account for fatigue in composites consisted in adapting to composites, the already existing methods for metallic materials [68]. Unfortunately, the situation regarding the fatigue behavior of composite materials is different from that of metals and alloys. The methods developed for metallics are unsuitable and strongly not recommended for composites, as will be explained in the first section of this paper. Thus, in order to develop fatigue models for composite materials and to achieve a more optimized design and selection of materials, it is first necessary to understand the damage mechanisms and failure modes to propose models suitable for either conventional laminates or woven composite structures. However, as mentioned in [5], it is "difficult to get a general approach of the fatigue behavior of composites materials, including polymer matrix, metal matrix, ceramic matrix composites, elastomeric composites, Glare, short fiber reinforced polymers and nano-composites".

Research on the fatigue performance of advanced composites started at the beginning of the 70s, just after their introduction and first applications. A lot of experimental work has been performed over the last four decades for fiber-reinforced composites and very comprehensive databases have been constructed, particularly concerning wind power applications [34]. Along with these experimental works, theoretical models have been developed to predict damage accumulation and fatigue life for fiber-reinforced composites with various stacking sequences and fiber- and matrix-types under loading conditions that vary from constant-amplitude loading to spectrum loading [4, 20, 28, 38, 57, 58, 77]. A classification of these models will be presented further in this paper. Despite all of these studies, research efforts should be continued to meet the challenge of developing models with a more generalized applicability in terms of loading conditions and of material selection.

How should the issue of fatigue be addressed for composite materials?

Fatigue in materials is caused by repeated loading and unloading cycles to maximum stresses lower than the ultimate tensile strength of the material. Cycling loading and the different loading regimes are characterized by the R-ratio ($R=\sigma_{min}/\sigma_{max}$) as reported in figure 1.

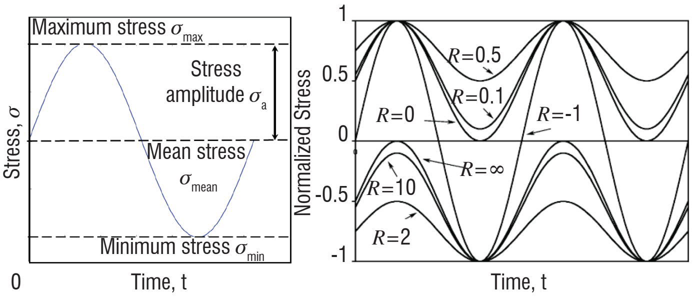

Figure 1 - Sinusoidal loading and relevant terminology of different loading R-ratios from Post et al.[59]

Metals vs. composite materials

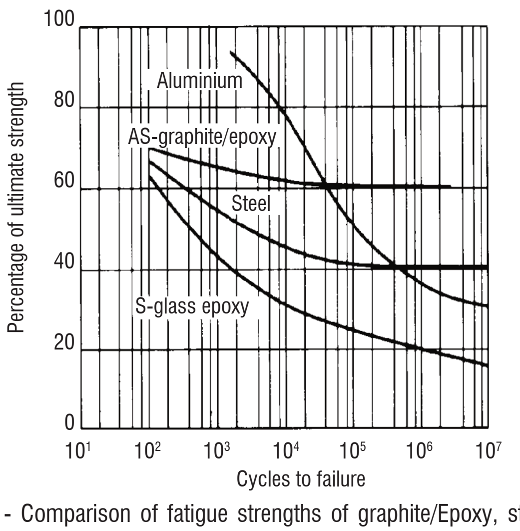

Figure 2 - Comparison of fatigue strengths of graphite/Epoxy, steel, fiber-glass/Epoxy and aluminum from Weeton et al. [91]

As mentioned previously, metals and composites behave differently under fatigue loading. Bathias [5] devoted an entire paper to the comparison of fatigue damage between metals and composite materials, and pointed out some important differences between metals and high performance composites. The main differences are summarized as follows. Composite materials exhibit a better resistance to fatigue, compared to metals. The fatigue ratio, S_D/UTS, between the fatigue strength, S_D, in tension-tension ($0<R<1$) and the ultimate static tensile strength, UTS, is always higher than 0.4 and can reach 0.9 for CFRP (Carbon Fiber Reinforced Polymer). These values are comparable to those found for metals, i.e., less than 0.5, and only 0.3 for aluminum alloys (Figure 2).

However, despite their high fatigue performances, composites are not totally sheltered from fatigue damage, due to, essentially, the variety of configurations (types of fiber, resin and lay-up) that can result in different endurances. Figure 3 shows a comparison of various architectures with regard to fatigue performance.

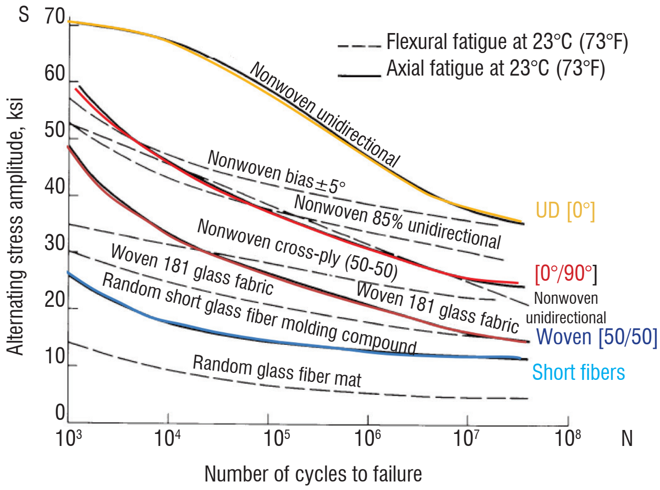

Figure 3 - Comparative fatigue strengths of a same resin/Glass composite with various fiber architectures (UD, woven, laminates) from Weeton et al. [91]

A difficulty with composite materials is that increasing fiber resistance or matrix toughness, or even improving fiber/matrix bonding, does not always result in an improved fatigue performance, i.e., a longer fatigue life and a higher fatigue ratio [40].

The fatigue resistance of composite materials is much lower in compression–compression ($R>1$) than in tension-tension ($0<R<1$), whereas it is the contrary for metallic alloys. Tension-compression fatigue is more deleterious than tension-tension fatigue and is the most detrimental loading condition for fatigue of composites. Note that the ratio S_D/UTS under compressive loading can be as low as 0.3 for some composite materials. Under bending, the behavior of composite materials is difficult to determine because of the multitude of types of damage that occur (transverse cracks due to tensile loading, delamination, fiber kinking due to compression loading). As a result, the fatigue of composite materials is a complex phenomenon. For instance, even if the compressive strength of a composite is generally lower than the tensile strength and the composite is less damaged under compression loading, an effect of the tension damage on the compressive strength can be observed.

The comparison between damage accumulation in composite materials and in homogeneous materials, as a function of the number of cycles, is schematically described in figure 4. A relatively large part of the total fatigue life in metals is devoted to the stage of gradual and invisible deterioration (i.e., mesoscopic scale damage, such as: dislocation cells, persistent slip bands (PSB), etc.). There is no significant reduction of stiffness in metals during the fatigue process. The final stage of the process starts with the formation of small cracks, which are the only form of observable damage. These cracks grow gradually and coalesce quickly to produce a large crack leading to final failure of the structural component [86].

During fatigue of composites, damage starts very early, after only a few hundred loading cycles or even during the first loading cycle for a high stress level. This early damage is followed by a second stage of very gradual degradation of the material, characterized by a progressive reduction of the apparent stiffness. More severe types of damage appear in the third stage, such as fiber breaks and unstable delamination growth, leading to an accelerated decline and, finally, to catastrophic failure [86].

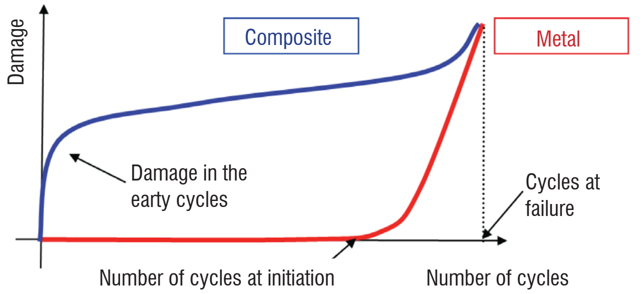

Figure 4 - Comparison of the damage evolution as a function of the number of cycles for composites and metals.

All of these differences between metals and composite materials lead to developing specific methods for modeling the fatigue behavior of each material. Usually, methods for predicting the damage initiation are sufficient for metals, whereas it is necessary to follow the evolution of the different damage mechanisms in composite materials and to be able to estimate the effect of these different damage modes on the material behavior and failure (residual performances). Consequently, methodologies developed for metals are not suitable for composite materials. In order to develop specific methods for composites, it is thus imperative to understand their fatigue damage mechanisms.

Fatigue damage mechanisms in composite materials

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

During fatigue, the first stage of deterioration of continuous fiber-reinforced polymers is characterized by the formation of a multitude of microscopic cracks and other forms of damage, such as fiber/matrix interface debonding and fiber pull-out from the matrix. As mentioned earlier, during fatigue, damage starts very early (Figure 5 a-b). During this initial loading period (Stage 1), there is generally a small drop in stiffness associated with the formation of damage. Then, there is a second stage of very gradual degradation of the material, where the stiffness reduces progressively and where damage seems to increase slowly and linearly. More serious types of damage appear in the third stage, such as fiber breakage and unstable delamination growth, leading to an accelerated decline with an increasing amount of damage and finally catastrophic failure [23]. Schulte et al. [71-73] first reported this three-stage stiffness reduction and it has, since then, been observed in many different types of composite materials, and also in woven composites [22, 93].

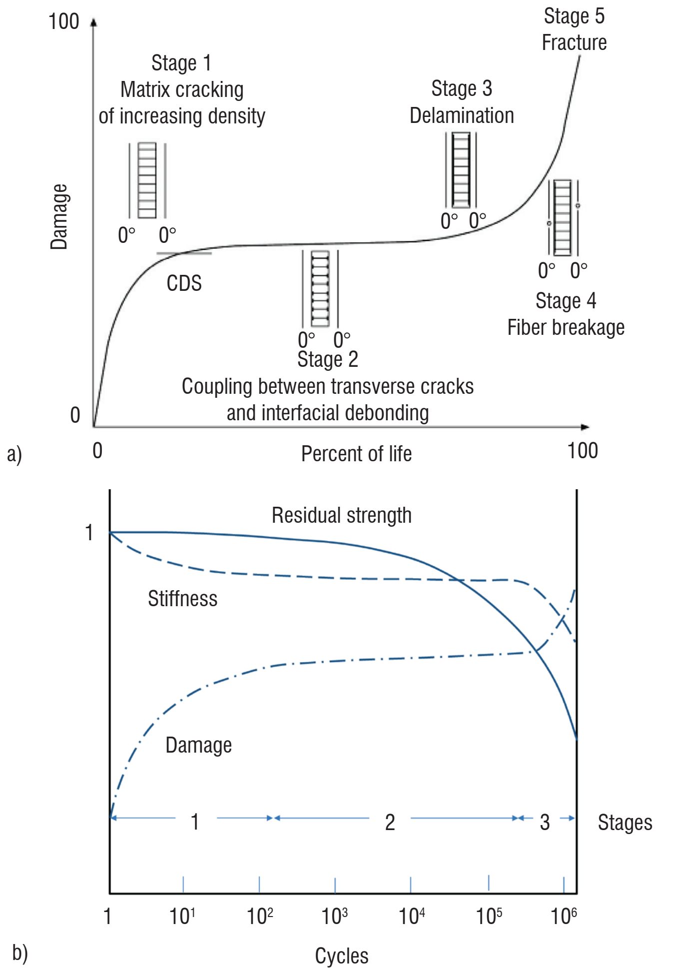

Figure 5 - a) Fatigue crack growth in cross-ply laminates and b) the three characteristic stages of fatigue damage in composites from Reifsnider [62]

Several authors have shown that the observed damage mechanisms are identical for laminates under static and fatigue loadings [66, 85, 90]. However, the crack evolution laws are different and the damage threshold in fatigue is lower than the damage threshold during static loading [7, 8, 42].

Another type of composites, such as woven-fabric composites, is showing growing interest and is used in advanced structural applications due to its inherent advantages. Indeed, the advantages conferred by the woven reinforcements compared to fiber lay-ups are an easier manipulation and ply stacking during composite manufacturing, good drapability properties that allow the use of woven reinforcements in complex mold shapes, increased impact resistance and damage tolerance of the composite material and delamination resistance capability owing to the presence of fibers along the thickness direction. Along with these advantages, composite materials based on woven fabric reinforcements achieve high stiffness and strength, comparable with those obtained through traditional fiber reinforcements.

In 2D woven composites (fabric formed by interlacing the longitudinal yarns (warp) and the transverse yarns (weft)), such as plain, twill or satin), four types of damage mechanisms occur under static and fatigue loadings: intra-yarn cracks in yarns oriented transversely to the loading direction, inter-yarn decohesion between longitudinal and transverse yarns, fiber failure in longitudinal yarns and yarn failures [9, 11, 52, 54, 82, 85].

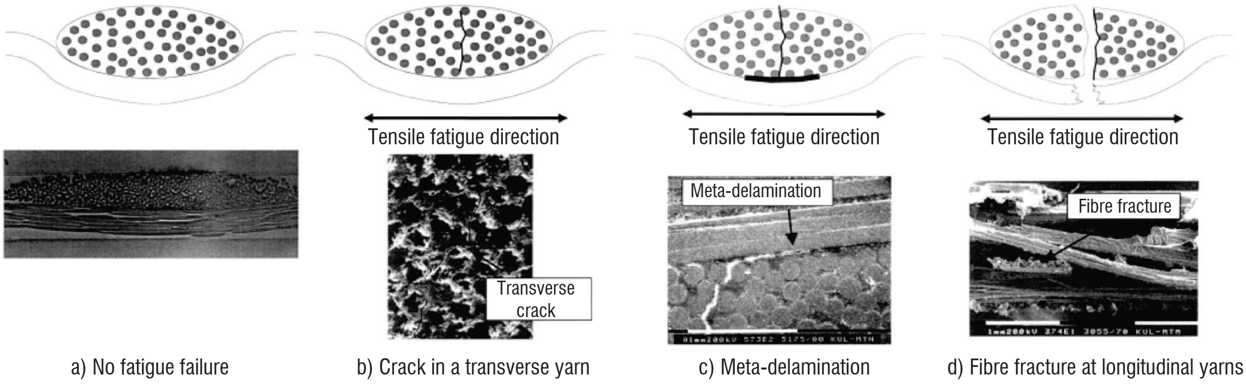

Figure 6 - Scheme of the tensile fatigue damage development in woven fabric composites, subjected to a tension–tension fatigue loading in the weft direction from Pandita et al. [54].

A damage scenario consisting in four stages can be deduced from these works (Figure 6) and has been proposed by Pandita et al. [54]. Under fatigue loading, for a plain-weave fabric composite subjected to a maximum tensile fatigue load of 0.5 of the static strength in the on-axis direction, there is no or very little fatigue damage in the first stage (Figure 6a). In a second stage, fatigue damage consists of fiber-matrix debonds and matrix cracks in transverse yarns, leading to a continuous transverse crack (Figure 6b). This transverse crack subsequently grows either into a matrix-rich area or is deflected into the longitudinal fiber bundle within the same layer, a phenomenon called 'meta-delamination' (Figure 6c). It constitutes the third stage, characterized by a saturation of intra-yarn cracks. The propagation of the transverse cracks proceeds very slowly. The fourth stage (Figure 6d) consists in the separation between the longitudinal yarns. Finally, in 2D woven fabrics, static and fatigue damage mechanisms are similar, the only difference concerning the damage evolution laws.

The geometry of 3D or interlock woven composites and composites with braided reinforcement is so complex that it is generally difficult to clearly separate the occurring damage mechanisms: microcracking, interface failure, void initiation and void growth. A major difference, compared to composite laminates or 2D woven composites, is that delamination is impeded. During static loading, the observed damage mechanisms are intra-yarn cracks in transverse yarns, inter-yarn debonding between longitudinal and transverse yarns, fiber failure in longitudinal yarns and failure of the yarns. These 3D woven composites, which have very good mechanical properties - improved through-thickness elastic properties, resistance to delamination and to impact damage - present similar static and fatigue mechanisms, as observed experimentally [31, 69].

To summarize, while damage mechanisms are really different between UD laminates and woven composites, in both cases, these damage mechanisms are comparable under either a static or a fatigue loading. The only change is in the damage evolution laws.

Fatigue damage modeling

State of the art

As mentioned earlier, fatigue studies started mainly with experimental campaigns during the 70s in the aerospace field to demonstrate that fatigue was not a real issue at that time. Some experimental campaigns are still conducted nowadays. For example, an extensive material testing program, the OPTIMAT research program [34], was conducted recently over 3000 individual tests over four years. Testing has been focused on the mechanical properties of the composite materials commonly used in modern wind turbine blades, specifically epoxy GFRP (Glass Fiber Reinforced Composite). However, experimental tests are expensive and it is difficult to cover all of the configurations.

In order to reduce the number of tests for predicting composite fatigue failure, composite fatigue modeling is required. An interesting article written by Degrieck and Van Paepegem [17] focuses on the existing modeling approaches for the fatigue behavior of fiber reinforced polymers and gives a comprehensive survey of the most important modeling strategies for fatigue behavior. A more recent paper written by Sevenois and Van Paepagem [76] gives an overview of the existing techniques for fatigue damage modeling of FRPs with woven, braided and other 3D fiber architectures. The aim of the present paper is not to give an in-depth discussion of the fatigue models; thus, the interested reader will be asked to refer to references [17, 76]. In the first reference, the authors justify the classification, currently made by Sendeckyj et al. [75], concerning the large number of existing fatigue models for composite laminates. This classification consists of three major categories: fatigue life models (empirical/semi-empirical models), which do not take into account the actual degradation mechanisms, but use S-N curves or Goodman-type diagrams and introduce a fatigue failure criterion; phenomenological models for residual stiffness/strength; and, finally, progressive damage models (or mechanistic models), which use one or more damage variables related to observable damage mechanisms (such as transverse matrix cracks, delamination). Note that this classification has been recently slightly modified for fatigue damage modeling techniques for FRP (Fiber Reinforced Polymers) with woven, braided or other 3D fiber architectures [76], but the classification reported in the following refers to [17].

Empirical or semi empirical models quantify failure or determine the composite fatigue life based solely on a fixed loading condition (i.e., the stress state). These experimentally based models are all specific to certain types of composite materials and do not consider specific damage mechanisms in their formulation. They require extensive and expensive experimental campaigns and are difficult to extend towards more general loading conditions. This methodology is traditionally used by industrialists. Various models can be found in the literature [12, 19, 20, 28, 63]. As shown in figure 7, (semi) logarithmical formulations can be used as well as numerous other S-N formulations; some of them are reported in figure 7.

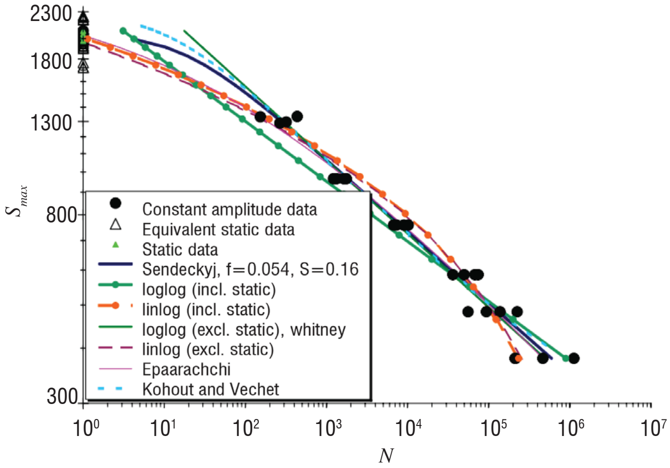

Figure 7 - Various constant amplitude S-N curve fits for $(0°)_8$ glass/epoxy, R=0.1 [50]

Phenomenological models describe the fatigue behavior of the composite through the evolution of macroscopic properties, such as stiffness [39, 56, 81] and strength [16, 36, 65, 78]. The loss of these macroscopic properties is usually described. Residual strength models possess a natural failure criterion (Figure 8): if the residual strength falls to about the same level as the externally applied stress, then, the material fails [26]. However, it necessitates destructive tests. Empirical models and residual strength models cannot be used to simulate the stiffness degradation during fatigue life because both S-N fatigue life methodology and residual strength approach do not take into account the loading history, i.e., the successive damage states, the continuous redistribution of stress and the reduction of stress concentrations that appear during the gradual degradation of a fiber-reinforced composite in a structural component. Residual stiffness models describe the degradation of the stiffness properties due to fatigue damage in terms of macroscopic variables, but they exhibit much less statistical scatter than residual strength models.

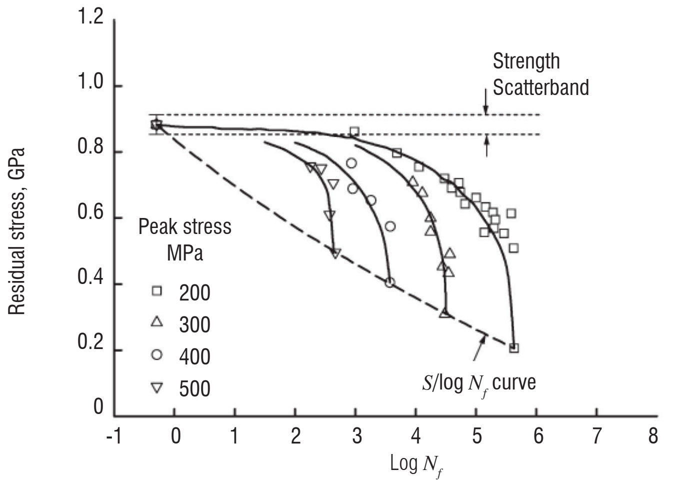

Figure 8 - Residual strength curves for 0/90 GRP laminate samples subjected to fatigue cycling at an R ratio of 0.1 and various stress levels [24]

Progressive damage models, which use one or more damage variables related to measurable effects of damage (interface debonding, transverse matrix cracks, delamination size, etc.), are claimed as the most promising models because they quantitatively account for the damage accumulation in the composite structure. Degrieck and Van Paepegem [17] subdivide progressive damage models into two classes:

• Damage models that predict the damage growth as such (e.g., number of transverse matrix cracks per unit length, size of the delaminated areas). These models consider one specific damage mechanism and determine the physical change in damage with increasing loading cycles. They are typically of the form of the well-known Paris' law for crack propagation in homogeneous materials (i.e., da/dN). References, essentially on fatigue of composite laminates, can be found in [6, 21, 30, 70].

• Models that correlate the damage growth with the residual mechanical properties (stiffness/strength). One of the major causes of the stiffness degradation is distributed matrix cracking, and such a type of progressive damage suggests the use of a continuum damage model to describe the material behavior [41, 43, 46, 83]. These models typically use Finite Element models to simulate the damage progression and some of them have been extended to predict the fatigue life of a structural component. Among the various studies on laminates, different contributions must be quoted: [1, 2, 13, 44, 45, 51, 67, 74, 79, 80, 84]. Most of these works concern fatigue of laminate composites. A few research groups deal with fatigue of woven composites. Among them, Hochard et al. [32, 33] developed a fatigue damage approach as a combination of a static damage model and a cumulative damage evolution law based on a thermodynamic approach. Modeling both static and fatigue loadings with the same model is allowed by the use of a non-linear cumulative law that describes the damage evolution according to the maximal load and the amplitude of the cyclic loading. This model is based on a damage model developed for UD carbon/epoxy laminates [55]. Thanks to the assumption consisting in replacing the woven ply by two stacked unidirectional virtual plies, this generalized model can be used to simulate the mechanical behavior of various unbalanced woven plies, from quasi-unidirectional to balanced woven plies. This model has been applied with success to a 5-harness satin weave glass/epoxy laminate without stress concentration. Nevertheless, a plane stress assumption is made and this model cannot be directly applied to thick 3D woven composites.

A damage model has also been proposed by Van Paepagem et al. [87, 88] and is based on anisotropic damage evolution functions with separate terms for the damage initiation, the damage growth and the final progressive damage evolution. This model can simulate stiffness damage, stress redistribution and accumulation of permanent strain. The use of a modified Tsai-Wu static failure criterion has been proposed. The fatigue damage model has been applied to displacement-controlled bending fatigue experiments of plain-weave glass/epoxy specimens and good agreement was found between predicted and simulated specimen deformation and applied force.

These two models have been developed for 2D woven composites and not for 3D woven interlock composites. The plane stress assumption cannot be applied [61], since these composites are relatively thick.

An important feature of these degradation approaches is that they enable variable amplitude loadings to be dealt with, since they can take into account a change of stress state during loading. Actually, traditionally, fatigue characterization of a material is performed under constant amplitude sinusoidal loading and most experimental studies of variable amplitude loading in composite materials have focused on loading that consists of two or more constant amplitude blocks with two to four stress levels and R-ratios [27, 53, 92]. Nevertheless, the block loading tests are not representative of realistic loading situations and may not even generate the same type of damage state in the material. The majority of the models presented in the literature have only been applied to constant amplitude loading and block loading with a few stress levels. The reader is referred to a comparative study presented in [59] that evaluates different models in terms of their predictive capability under more realistic spectrum loading cases of interest to the wind turbine and naval architecture industries.

ONERA fatigue damage modeling of 3D woven interlock PMC and CMC composites

ONERA has been working for years on progressive damage models under static loading of 3D polymeric and ceramic woven composites (ONERA Damage Model (ODM) [46, 48]). These two models accurately describe the static behavior of either 3D woven polymer matrix composites (PMC) or ceramic matrix composites (CMC). Recently, they have been extended to fatigue loadings [29, 61]. As mentioned previously, in the case of interlock woven PMC, the same damage mechanisms occur during monotonic and fatigue loadings, but their damage evolution laws differ. These damage mechanisms are described using damage variables that describe the effects of damage on the behavior in the three main directions of the woven composite. Then, a cumulative damage d_k, per k mechanism (k=1, 2 or 3), is defined by adding two terms: one part is due to the monotonic loading d_k^{Mon} and the other one is governed by fatigue loading d_k^{Fat}. The monotonic damage law depends on the driving forces y_k which are themselves a quadratic form of strain: $y_k = fct(\varepsilon)$. This leads to a scalar (instead of a tensor) formulation, which is easier to analyze and to generalize to multiaxial loadings. The matrix damage driving forces for monotonic loading are also assumed to drive the matrix damage during fatigue loading:

$$d_k = d_k^{Mon}\left(\sqrt{y_{Max}}\right) + d_k^{Fat}\left(y_{Max}, R_{yk}\right) \tag{1}$$

The cyclic damage law, where N is the number of cycles, includes the description of the matrix damage evolution during cyclic loading:

$$\frac{\delta d_k^{ü}}{\delta N} = \left(d_{\infty(k)} - d_k\right)^{\gamma_k} \left(\frac{\left\langle \left(1 - ü_{yk}\right)^{\beta_k} {}_{Max(k)} - {}^{ü}_{0(k)} \right\rangle_+}{y^{ü}_{c(k)}} \right)^{\delta_k} \tag{2}$$

$$R_{yk} = \begin{cases} \dfrac{y_{min(k)}}{y_{Max(k)}} & if\ y_{Max(k)} > 0 \\ 0 & else if \end{cases} \tag{3}$$

R_y evolves between 0 and 1 since the driving forces are always positive. Moreover, this specific ratio definition is very convenient to deal with multiaxial loadings. Note that when the stress ratio is negative $R_\sigma < 0$, the corresponding driving force ratio is null (because $y_{min} = 0$ when $R_\sigma < 0$). Rakotoarisoa [61] does not take into account the behavior for compressive loadings in the model; consequently, the damage evolution is only possible for tension (static or fatigue) loadings (thus, only for positive stress ratios). $y_{0(k)}^{Fat}$ is the fatigue damage threshold, $y_{Max(k)}$ is the maximal driving force (maximum over one cycle) and $y^{ü}_{c(k)}$, γ_k, β_k, δ_k are model parameters. At saturation, the damage reaches the saturation value $d_{\infty(k)}$. This model has been validated on smooth specimens and a good agreement was found between experimental data and simulation. Variable amplitude loadings can be described with this model, even creep loading cases, except spectral loading, in which all cycles have a different load evolution. To address these complex loadings, a 3D kinetic damage model for woven PMC composites, i.e. with a rate form written damage evolution laws ($\partial d / \partial t = \ldots$), is currently under development in collaboration with LMT-Cachan [3] based on the ODM-PMC model. A specific feature of the proposed damage law is that it only introduces one damage variable per mechanism, but with two contributions (a monotonic contribution and a fatigue contribution). The kinetic damage evolution law can be applied to different kinds of loading (monotonic, fatigue, random) and is also mean stress dependent [18]. The final damage evolution law recovers the initial cumulative damage ODM-PMC model exactly in cases of monotonic and creep loadings.

Concerning the yarn failure (due to fiber failures), even though the fibers are usually assumed to be insensitive to fatigue loadings [82], matrix damage leads to load transfer to the fiber bundles leading to fiber failure, thus inducing a reduction in the effective strength of the fiber bundles. Finally, fiber bundle fracture is used as a criterion for the evaluation of fatigue lifetime, as well as residual strength. The rupture is induced by a sudden and unstable multiplication of fiber failures in the yarns. These yarns can be considered as the critical element in the sense of Reifsnider [64], since their failure defines the composite failure. There is no first sign of damage for the yarn (loss of modulus) because early failures are limited and spatially dispersed.

Fatigue of CMC woven composites is also a new subject of interest in the community [15, 60]. CMC woven composites can be used in the aerospace industry, because of their low mass density and good mechanical properties at high temperature, since they are protected against oxidation by a self-healing matrix at temperatures higher than 650°C. A fatigue model, based on the ODM model specifically devoted to CMC woven composites (five damage variables, since damage is oriented by the loading [47], instead of three variables for PMC woven composites for which damage is mainly oriented by the microstructure) has been developed at ONERA [29, 49]. The lifetime of the material is determined through a macroscopic mechanical model and a physicochemical model, which is time-dependent. The procedure has been validated considering SiC/SiC specimens under fatigue loadings and subjected to different kinds of environment, i.e., pressure (oxygen and water) and temperature.

Structural simulation

These two models have been implemented in a finite element code (ZeBuLoN), in order to (i) keep track of the continuous stress redistribution (the simulation requires the complete path of damage states to be followed) and (ii) to perform fast and efficient finite element simulations.

Figure 9 presents the modeling strategy to determine the fatigue life and residual strength of interlock woven PMC composites. A first static analysis is performed with the quasi-static model to verify whether the specimen has failed or not. If it is not the case, a first set of cycles is applied. The cumulative damage law allows the resulting matrix damage variables to be calculated. Then, before ensuring that the bundle failure criterion is not attained, in order to perform the next block of cycles, the strain fields, fiber bundle fracture variables and matrix damage driving forces are updated by simulating one cycle (shown in red in figure 9) with the quasi-static model. To reduce the computational costs of the model, the updating is performed at three characteristic load levels only: maximum and minimum load are

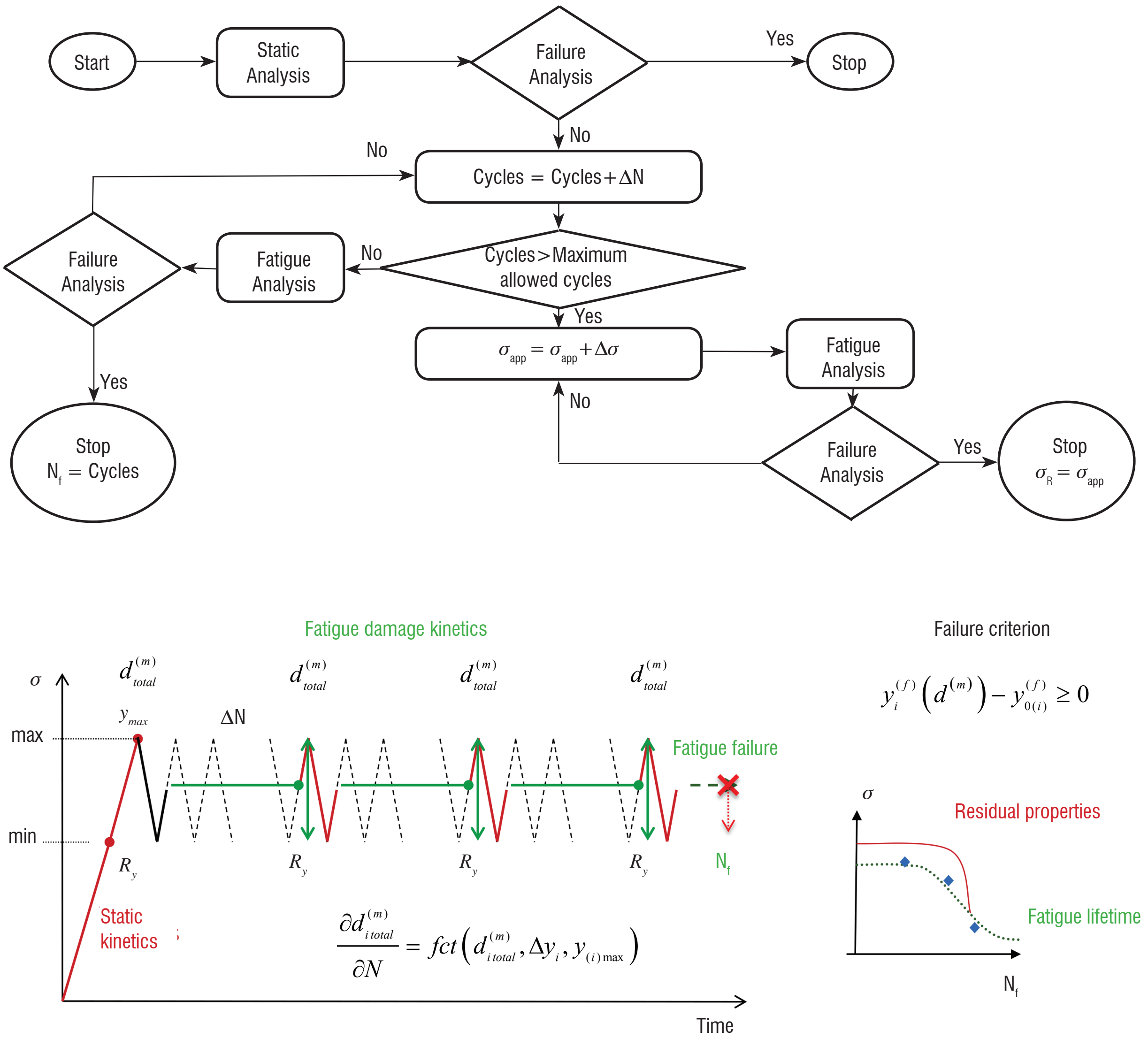

Figure 9 - Modeling strategy for lifetime and residual strength prediction

chosen in order to calculate the parameters required for the failure analysis and the next fatigue analysis. The mean load is chosen in order to estimate the evolution of viscous strain. This method can be considered as an adapted version for composites of a jump-in-cycle procedure. The value of the "cycle jump" can be determined by an automated criterion [45]. The damage variables are used as a measurement for determining the size of the block of cycles. The faster the damage evolution is, the smaller the blocks are and, consequently, the number of cycles per block. Moreover, the larger the number of cycles used to update the driving forces is, the longer the finite element fatigue life simulations are, since the updated cycle needs to be finely discretized. This model has been applied to open-hole specimens, but the simulation results still need to be compared with experimental data.

Constant life diagram

Generating fatigue data for every configuration as a basis for efficient predictive models is not conceivable. Constant life diagrams (CLD) offer a predictive tool for the estimation of the fatigue life of the material under loading patterns for which no experimental data exist. It is a representation of S-N data. The constant-life lines in the CLD connect points with the same estimated lifetime, as a function of mean stress and stress amplitude.

Constant life diagrams for metals are usually observed to be symmetric, whereas for composites they are distinctly not, due to the different tensile and compressive strengths that they exhibit. Actually, in fatigue, there are different damage and failure mechanisms in tension and compression. Under tensile loading, the laminate composite is governed by fiber failures (in a fiber-dominated lay-up). Under compression loading, the composite properties are mostly determined by the matrix and matrix-fiber interaction. As a result, a typical CLD for composite materials is often shifted to the right hand side and the highest point is located away from the $R = -1$, ($\sigma_{mean} = 0$) line, as shown in figure 10.

Vassilopoulos et al. [89] have examined the influence of the formulation of a CLD on the composite lifetime. The predictive accuracy of the constant life formulation is very important because fatigue analysis results are significantly affected by the accuracy of the estimated S-N curve. They assessed the most common and recent formulations considering the ease of application, the need for experimental data and forecast accuracy, as critical evaluation parameters. The main highlights are given in the following.

On the adjustment of non-linearity (Figure 10), several approaches have emerged, i.e., piecewise linear "R-value multiple CFL diagram" [50], power law [25], power law from a single S-N experimental curve [37]and different power laws in tension and compression [10].

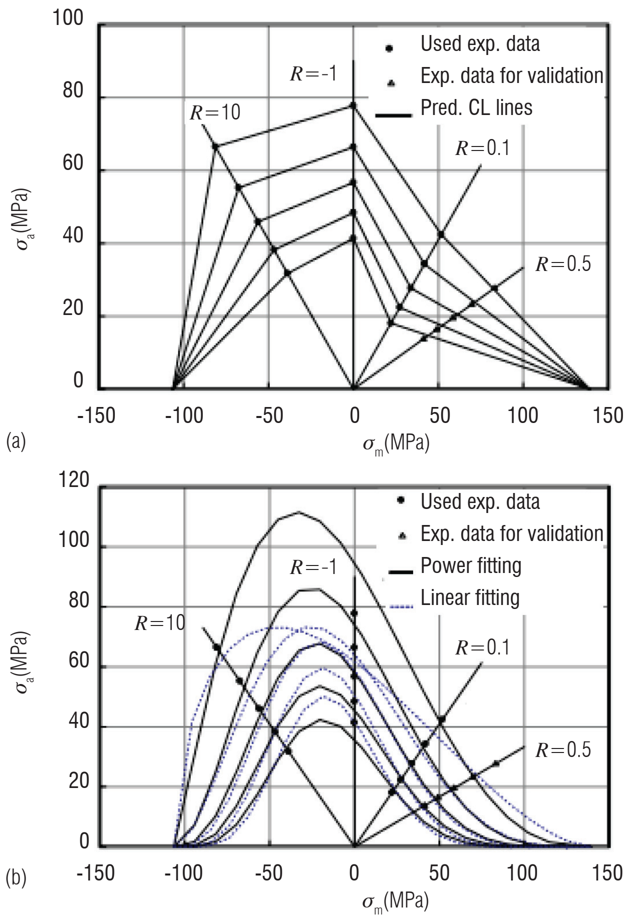

Figure 10 - Different types of CLD:
a - « multiple R-value CFL diagram »[50], b – power law [25]

Concerning the need for experimental data, the most demanding approaches have proven to be the most reliable. This is the case of the piecewise linear approach, which is the most accurate among the various formulations analyzed when a minimum number of three available S-N curves is available. The simplifying assumptions that allow some models to expect only a few fatigue data [37] or none [35] do not lead to a satisfactory accuracy. Moreover, these assumptions do not usually allow new fatigue measures to be incorporated “on the fly”. Finally, it should be noted that all of these approaches raise the question of a joint processing of static and fatigue data.

Uncertainties and variability

An inherent characteristic of composite materials, which must be taken into account, is the variability in strength and fatigue life data. This variability is higher than that observed in metals. The structural reliability provided by the conventional deterministic design approach (using safety factors) is different for composite and metal structures. Composite structures have to be designed with the same level of confidence as metallic structures and, therefore, a probabilistic-based methodology is of interest. In addition to the scatter in strength and life data, the uncertainties of the applied loads also affect the reliability of a structure. To deal with these uncertainties, a safety factor of 1.5, traditionally used in aircraft structural design, generally provides a very high level of reliability although not quantifiable. A probabilistic certification method can provide additional and useful information for a more efficient structural design. Recent works at ONERA have illustrated the implementation of an advanced probabilistic treatment by applying it, as a beginning, to simple empirical models. The approach is based on the SLERA principle (Strength-Life-Equal-Rank Assumption), which considers the static data dispersion as the main source of the whole observed dispersion [14], as presented in figure 11. The tools developed for the statistical identification are well adapted to the available types of data (lifetimes, static / residual strengths) and their structuring. They are based on the innovative use of the EM (Estimation-Maximization) algorithm. This allows the identification to be made more versatile and more effective compared to techniques in the available literature. Its application to purely numerical fatigue models is still in progress and will incorporate the already available numerical techniques for propagating uncertainty.

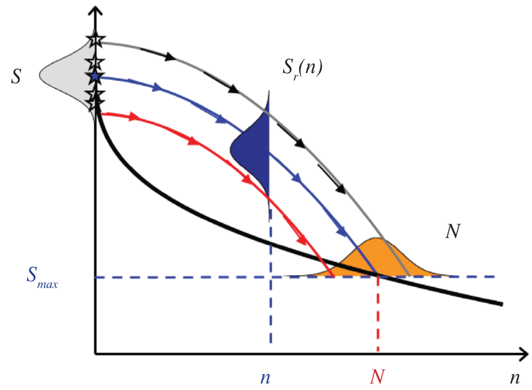

Figure 11 - SLERA principle (Strength-Life-Equal-Rank Assumption)[14]

Conclusion / Perspectives

This paper has attempted to address the problem of fatigue life prediction of composites from the point of view of ONERA. It describes the methodology that ONERA adopted to propose a fatigue life modeling. In this respect, ONERA has taken advantage of years of experience in progressive damage models under monotonic loadings, both for laminates and 3D woven composites. Nevertheless, studies on fatigue of composites are relatively recent at ONERA, less than five years. The first idea was that ONERA would benefit from a good knowledge of fatigue of metallics, in order to propose a fatigue model for composites; however, as reported in the first part of this paper, the fatigue methodologies for metallics cannot be directly applied to composites. It has also been shown that the composite fatigue failure modes are different depending on the type of composites (2D or 3D woven, UD laminates). There is no single method for the modeling of a series of composite materials. To propose a fatigue model for 3D interlock woven composites (PMC or CMC), the initial important step for ONERA consisted in understanding the damage mechanisms occurring in woven composite materials during fatigue. It resulted from this study that the types of damage mechanisms in 3D interlock woven composites resulting from monotonic or fatigue loadings are fairly similar. This then allowed the existing monotonic damage models to be extended to a fatigue model. These models have been applied to simple structures and the next step will consist in applying them to real structures under real loadings. This constitutes a challenging perspective to this study.

Acknowledgements

The collaboration with Snecma and Herakles is gratefully acknowledged. This work was partly supported under the PRC Composites, a French research project funded by the DGAC, involving SAFRAN Group, ONERA and CNRS. The authors would like to express their sincere gratitude to Dr. R. Valle for valuable and helpful discussions.

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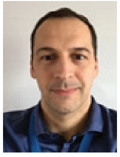

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