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Woodhead Publishing Series in Composites Science and Engineering: Number 53

Fatigue of Textile Composites

Edited by

Valter Carvelli and Stepan V. Lomov

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Woodhead Publishing is an imprint of Elsevier
80 High Street, Sawston, Cambridge, CB22 3HJ, UK
225 Wyman Street, Waltham, MA 02451, USA
Langford Lane, Kidlington, OX5 1GB, UK

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Control Number: 2015932577

ISBN 978-1-78242-281-5 (print)
ISBN 978-1-78242-293-8 (online)

List of contributors

Y. Abdin KU Leuven, Leuven, Belgium

P. Abel Institut für Textiltechnik (ITA) of RWTH Aachen University, Aachen, Germany

A.N. Anoshkin Perm National Research Polytechnic University, Perm, Russia

P. Brøndsted Technical University of Denmark, Risø Campus, Roskilde, Denmark

P.A. Carraro University of Padova, Vicenza, Italy

V. Carvelli Politecnico di Milano, Milan, Italy

T. Gries Institut für Textiltechnik (ITA) of RWTH Aachen University, Aachen, Germany

M. Gude Institute of Lightweight Engineering and Polymer Technology – ILK, Dresden, Germany

A. Jain KU Leuven, Leuven, Belgium

M. Kawai University of Tsukuba, Tsukuba, Japan

I. Koch Institute of Lightweight Engineering and Polymer Technology – ILK, Dresden, Germany

C. Lauter Automotive Lightweight Design (LiA), University of Paderborn, Paderborn, Germany

S.V. Lomov KU Leuven, Leuven, Belgium

A.P. Mouritz RMIT University, Melbourne, VIC, Australia

M. Quaresimin University of Padova, Vicenza, Italy

M. Ricotta University of Padova, Padova, Italy

R. Talreja Texas A&M University, College Station, TX, USA

T. Troester Automotive Lightweight Design (LiA), University of Paderborn, Paderborn, Germany

K.A.M. Vallons KU Leuven, Leuven, Belgium

W. Van Paepegem Ghent University, Gent, Belgium

A.P. Vassilopoulos Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

J. Xu KU Leuven, Leuven, Belgium

J. Zangenberg LM Wind Power Blades, Materials and Processes, Kolding, Denmark

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Preface

Structural components are often exposed to cyclic loading throughout the lifetime, and these cyclic actions degrade the mechanical performance of the materials. The material degradation under cyclic loading is known as ‘fatigue’. The fatigue damage initiation and cyclic propagation may have severe consequence on the structural integrity and may lead to the structural collapse for stress amplitudes lower than the actual strength of materials. Fatigue of materials is a well-known engineering problem, and it was extensively and deeply investigated for metallic materials and structures.

Nowadays, lightweight structures are mainly manufactured with composite materials based on polymers reinforced with long continuous fibres, for weight reduction and for improving the mechanical performance. The anisotropic mechanical properties of composite materials can be designed to be higher, in relation to density, than those of metallic structural materials, and may be tailored to the requirements of the particular application. The inhomogeneous composite materials have architecture reinforcement dependence of the mechanical properties, which leads to a more complicated material description. As consequence, the damage mechanisms imparted by cyclic loading are coupled in the different material directions, and the fatigue theory for metals is inadequate.

The huge amount of research on fatigue of composite materials was mainly dedicated in the past decades to unidirectional laminated composites. Recently, the peculiar features of composite reinforced with technical textiles increased their application in lightweight structures. Moreover, the development of automated, computer-controlled machines for textile reinforcements industrial scale manufacturing and the increasing machine operation speed makes such preforms competitive from the productivity and affordability viewpoints. A huge variety of interlacement geometric architectures for composite reinforcements, ranging from two-dimensional (2D) to three-dimensional (3D) fabrics, are now available with excellent drapability and versatility, which is extremely important for complex double-curvature shape components. A deep understanding of the fatigue endurance of textile-reinforced composites is currently in high demand from industry for their potential application in structural elements subject to long-term fluctuating loads (e.g. automotive, aeronautical, marine, energy production, etc.).

The aim of this book is to focus on this particular aspect, the fatigue behaviour of textile composites, collecting together in one volume several different perspectives. The book presents recent developments on ‘fatigue response’ looking at the various methodologies that are currently available and at different scale levels. Experimental measurements, observations and numerical predictions for 2D and 3D textile-reinforced composites are discussed. Particular attention is also given in the final part on the use of textile composites in structural components, mainly those that are of specific industrial interest.

The book consists of four parts linking the knowledge on fatigue of textile composites at the micro, meso and macro level.

The first part gathers the fundamental principles necessary for studying the fatigue of composites, which serve as a framework for (more-narrow) textile composites. This part collects important concepts of fatigue of heterogeneous, hierarchically organised composites as opposed to 'metal' concepts, which are already well known in the engineering community. Experimental test methods and available extensive experimental databases are also covered.

Part Two presents the necessary starting point for studies on the fatigue behaviour of fibre-reinforced materials: the behaviour of the fibres themselves and of unidirectional fibre-reinforced composites. The former gives intrinsic fatigue behaviour of the fibres, which is of paramount importance, and the latter represents impregnated yarns in textile composites which is a necessary input for any modelling efforts or material design.

The third part collects experimental data on fatigue behaviour of textile composites reinforced with 2D and 3D textiles of both glass and carbon fibres. Particular attention is dedicated to the loading conditions, the environment effects and the damage evolution at macroscopic and microscopic level. The influence of 3D fibre architectures on the fatigue properties are also discussed and compared to 2D textile laminates. This part includes, moreover, an up-to-date on the growing field of modelling the fatigue behaviour of textile composites. There are already some established methods for woven laminates, but more detailed models are a subject of much controversy and discussion. The approaches given in these chapters represent the 'personal choices' of the Editors, but it should give a fair overview of the field.

The final part (Four) shows an overview of various textile composites applications where fatigue is an important design criterion. Application of textile composites in aeronautical, automotive, wind energy and construction engineering are presented with emphasis on fatigue life prediction and damage observation. This part of the book brings to a main conclusion on the importance of a synergetic design approach between modelling, testing and detailed damage inspection.

The book intend to fill the gap in the published literature and to provide a 'pivot point' for future research, which is currently much in demand due to the advancement and use of textile composites in industrial structural applications.

V. Carvelli
Politecnico di Milano, Milan, Italy
S.V. Lomov
KU Leuven, Leuven, Belgium

A conceptual framework for studies of durability in composite materials

1

R. Talreja
Texas A&M University, College Station, TX, USA

1.1 Introduction and background

Durability, understood as the ability to sustain mechanical or thermomechanical loads over a period of time, is in many structures a critical design consideration. The underlying processes responsible for loss of this ability can be rooted in time-dependent causes, such as viscoelasticity of polymers and stress corrosion cracking of fibers, or not explicitly in such causes but rather due to repeated (cyclic) application of loading over a period of time. In the latter case, the phenomenon is referred to as fatigue and is described with respect to some selected measure of load reapplication, such as the number of cycles of a sinusoidal load. This exposition will focus on durability in the context of fatigue in composite materials, but a brief treatment of a constant-in-time loading case will also be presented.

The first basic consideration in fatigue is concerning mechanisms triggered by load reapplication, that is, what happens in the second application of load that did not occur when the load was applied the first time. Clearly, if no difference exists, then there is total reversibility, which in the context of mechanical loading would be called elasticity. To be sure, apparent elasticity may be indicated by stress–strain behavior such that no measurable irreversibility (difference in loading and unloading responses) is seen at the (macro) scale of measurements, but irreversible processes (e.g., crack formation and permanent morphological rearrangements in a polymer) can be occurring at a smaller scale that are not yet significant to affect the macro scale response. Often, addressing the basic issue noted above presents challenges that do not seem surmountable, resulting in a resort to less fundamental approaches to fatigue.

A common type of approach to fatigue of materials—monolithic or composite—is to view it as a material property, the same way as elasticity, representing it by a number of material constants. These material constants are derived from the so-called S–N curve (or diagram) wherein the number of cycles of a constant-amplitude sinusoidal load needed to fail a material specimen is plotted against the applied stress amplitude (or stress maximum). The test data show significant scatter, unlike those for measuring elastic constants, and fitting a curve through average fatigue lives provides an empirical description of the fatigue properties. The entire fitted curve, or parts of it, are used to compare fatigue behavior of candidate materials for the purpose of material selection. For safety against fatigue in service environments, more empirical fitting of

Fatigue of Textile Composites. http://dx.doi.org/10.1016/B978-1-78242-281-5.00001-8

curves is needed, as the time variation of service-induced stresses differs from the standard sinusoidal stress variation used to obtain the $S-N$ curve. For example, if the reference testing is done with zero mean value of the sinusoidal load, then the fatigue properties at different nonzero mean stresses are related to the reference values by empirical means. This empirical approach originated in the field of metal fatigue in the nineteenth century and is known today as the "classical" approach. Modifications and additions to this approach came in the 1970s from the field of fracture mechanics, where stress analysis of cracks combined with energy considerations provided a means for addressing crack growth under cyclic loading.

The metal fatigue approaches have inevitably affected the studies of fatigue in composites. Simple reflection suggests that there is little justification for doing this. While the irreversibility underlying metal fatigue is rooted in crystal plasticity, this is hardly the case for composites, in particular for polymer-based composites. It would make more sense, therefore, to view composite fatigue on its own, divorced from metal-based ideas, and search for sources of irreversibility that are the characteristic of composite materials. This author attempted this approach and reported the results (Talreja, 1981). Since that early work, refinements have been reported in several subsequent works (Akshantala & Talreja, 1998, 2000; Gamstedt & Talreja, 1999; Quaresimin, Susmel, & Talreja, 2010; Talreja, 1982, 1985a, 1987, 1989, 1990, 1993, chap. 13, 1995, 1999, 2000, 2003, 2008; Talreja & Singh, 2012). Appropriately called a conceptual framework for interpretation of fatigue in composites, this approach will be described in some detail in this chapter.

The plan of what is to follow in this chapter is as follows. First, a discussion of material irreversibility will be presented where recoverable versus irrecoverable deformation will be clarified. Definitions of viscoelasticity and viscoplasticity will be put forth to facilitate reference to the sources of irreversibility. This will set the scene for describing accumulation of damage with load reapplication and the consequent fatigue failure. Fatigue life diagrams, introduced in Talreja (1981) as a conceptual framework for describing and interpreting fatigue behavior of composites, will follow from this discussion. With these diagrams as a backdrop, a mechanisms-based approach for predicting fatigue failure under general (multiaxial) time-varying loads will be outlined.

1.2 Fundamentals of material durability

As stated above, materials with full reversibility (same loading and unloading behavior) will remain durable as long as the reversibility holds. If time-dependent processes in the material behavior exist, then the aspect of recoverability must be considered. To clarify this, the following discussion is separated in loading cases that are described as constant-in-time and time-varying loads.

1.2.1 Constant-in-time loading

Consider a schematic stress–strain curve in Figure 1.1. It indicates three cases separated by their unloading response and labeled as A, B, and C. Case A is the

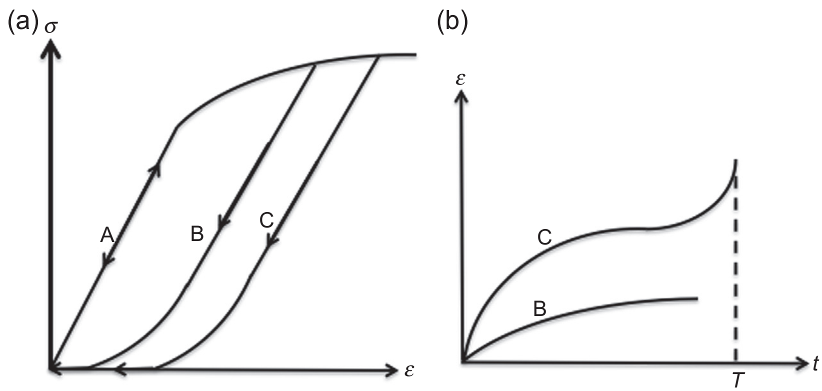

Figure 1.1 (a) Schematic stress−strain curves illustrating different loading−unloading behavior. (b) Time-variation of strain for cases B and C. A: reversible (elastic); B: irreversible with fully recoverable residual strain at unloading; and C: irreversible with partly recoverable residual strain at unloading.

reversible case with coincident loading and unloading paths. For simplicity, the stress−strain path shown for this case is linear, but in general it could be nonlinear, and if reversible, it would still represent elasticity of the material. Case B and Case C illustrate two cases in the inelastic (irreversible) regime of the time-dependent material behavior. In Case B the unloading path differs from the loading path, but on unloading to zero stress, the inelastic (residual) strain is fully recovered in time. In Case C, the residual strain is only partly recovered, leaving a permanent strain that indicates the nonrecoverable part of the internal material changes induced by loading. The differences in the material behavior between Case B and Case C are further illustrated in the strain−time response shown in Figure 1.1. In Case B, if unloading is not done, but instead the maximum stress reached is held constant, then the strain increases in time, as illustrated in the strain−time plot in Figure 1.1. This strain reaches a plateau, showing no further increase. In Case C, on the other hand, the strain at constant maximum stress increases in stages, characterized in increasing order by strain rates that are exponentially decreasing, constant, and exponentially increasing. The last stage leads to failure at time $t = T$, as indicated in the figure.

Case B and Case C illustrate the classes of material behavior described as viscoelasticity and viscoplasticity, respectively. Many polymers display these two types of behavior. At relatively low stresses, the induced molecular rearrangements increase in time until a limiting state is reached, and these rearrangements can be recovered by unloading. At higher stresses, the time-dependent behavior transitions to viscoplasticity, illustrated by Case C. Here, the molecular rearrangements get states of entanglements that cannot be fully recovered in time. Additionally, as stress increases, other permanent changes such as voids and cracks form. These changes can be self-intensifying, resulting in the exponentially increasing strain, as illustrated for Case C in Figure 1.1.

1.2.2 Time-varying loading

In nonmonotonic time-varying loads, the increasing parts of the loads induce internal material changes that would be recoverable if those changes are in the viscoelastic regime. However, if the decreasing parts of the loads do not allow sufficient time for recovery, then the residual changes will remain and could accumulate in subsequent loading—unloading excursions. The accompanying hysteresis in the stress—strain response will in this case indicate the strain energy available for dissipation (conversion) to other forms, for example, surface energy of cracks. Particularly in heterogeneous solids, such as composites, weak interfacial planes will be prone to separation (debonding) by absorbing the available strain energy. The presence of such internal surfaces will lead to the nonrecoverable part of the accumulated strain. The resulting material response will then be described as viscoplastic.

A note is in order concerning the use of the terms viscoelastic and viscoplastic. The labels "elasticity" and "plasticity" originate from metals where the underlying reversible and irreversible processes, respectively, are time-independent (instantaneous), except at high temperatures. The plastic deformation in metals is grounded in dislocation motion, and therefore the criteria for plasticity initiation (i.e., yield) and postyield behavior developed for metals cannot in principle be applied to polymers and polymer-based composites.

In fiber-reinforced polymer composites with relatively high fiber volume fraction, the time dependency in the polymer deformation is subdued and can often be neglected. Instead, the fiber/matrix interfaces, and the constrained matrix, are sources of surface formation and the consequent irreversibility in the stress—strain behavior. Due to the instantaneous nature of (brittle) crack formation for the most part, the time dependency in this process can also be ignored. With the "visco" in the viscoplastic out, one might call the irreversible time-independent processes in polymer matrix composites "plasticity." That would be inadvisable, however, particularly because of the confusion with metal plasticity, which, as noted above, is historically associated with dislocations in crystalline materials.

We shall adhere to the term "damage" for reference to distributed internal surfaces, which are the primary source of irreversibility in polymer matrix composites. The internal surfaces, and their formation and progression, induced by the loading—unloading excursions in the time-varying loading will be referred to as "fatigue damage." The rest of this exposition will focus on this phenomenon in fiber-reinforced composites.

1.3 A conceptual framework for fatigue durability

As argued above, the approach for determining fatigue properties by experimental data plotted as S—N curves is not an attractive proposition for composite materials. It is easy to see how this approach will become prohibitive when one considers the huge number of parameters involved, ranging from those related to load variation, for example, mean stress effect, load sequence effect, and varying load-amplitude effect, to those due to fiber volume fraction, fiber architecture, and lamination. Every change in combination of these parameters will call for testing. Alternatively, rules and formulas will be needed to derive fatigue properties for nonstandard cases, making use of large safety factors inevitable due to the uncertainty involved.

As an alternative to the empirical approach, this author proposed constructing a conceptual framework for describing composite fatigue behavior based on logical and systematical considerations of the underlying damage mechanisms (Talreja, 1981). Some key experimental observations help in "fixing" the basic pattern called "fatigue life diagrams," and it then becomes possible by logical analysis to extend these to other cases where the parameters related to loading and composite configuration change.

1.3.1 Fatigue life diagrams

The most basic case for illustrating these diagrams is unidirectional composites loaded in cyclic tension. The role of the constituents in this case must be analyzed first, as described below.

1.3.1.1 Primary role of fibers in composite fatigue

Consider a dry bundle of fibers loaded by a tensile force P, as illustrated in the sketch to the left in Figure 1.2. As is known, fibers produced commercially have defects resulting in their tensile strength over a given length being determined by the weakest point in that length. Thus, in a bundle of a given length where all fibers are parallel and of equal length and diameter, the fiber (or fibers) with the weakest point will fail first as the bundle is subjected to a tensile load P. Let $P = P_1$ be the value at which the first

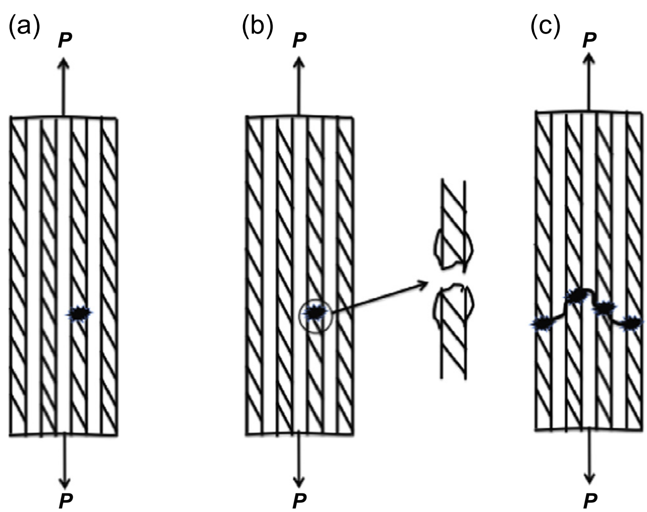

Figure 1.2 Fiber failure scenarios under a tensile load P. (a) A dry fiber bundle with the weakest fiber failure; (b) a fiber composite with the weakest fiber failure and debonding over a short length; (c) composite failure from linkage of failed fiber regions.

fiber failure occurs. At this load the surviving fibers in the bundle will instantaneously and equally share the load released by the broken fiber(s). If none of the surviving fibers fail at the new stress value corresponding to the applied load P_1, then on unloading and reloading the bundle no fibers will fail. In fact, assuming the fibers have no time-dependent failure process, any reapplication of the load P_1, any number of times, will not cause any more fiber failures. In other words, there will be no fatigue failure of the fiber bundle.

Consider now a composite consisting of a polymer matrix reinforced by the same bundle, and assume that all fibers in the bundle are perfectly bonded to the matrix. The axial tensile load P applied to this composite will at some load value $P = P_2$ cause the same fiber (or fibers) to fail first that failed also first in the dry bundle. However, the consequence of the fiber failure(s) in the composite will be quite different from that in the dry bundle case. Firstly, only the fibers in the immediate neighborhood of a broken fiber will carry the additional stress released by the broken fiber. Secondly, the broken fiber will debond locally from the matrix, as illustrated in the zoomed-in sketch next to the composite. Thirdly, the matrix surrounding the broken fiber ends will be stressed at a significantly higher level than prior to the fiber failure. Most importantly, at this new stress level, the matrix polymer will likely deform inelastically, producing the irreversibility that is the key to the fatigue process. Thus, unloading the load from P_2 and reloading to this value will now change the stress states in the matrix, as well as in the surrounding fibers in the close neighborhood to the broken fiber. Repeated application of this load can result in an accumulative process that can cause fatigue failure of the composite if a critical failure condition for composite failure is reached. A scenario for such criticality is sketched to the right in Figure 1.2, indicating failure from linkage of broken fibers in a local neighborhood of the weakest fiber.

In a unidirectional (UD) composite of a given volume V, the fiber defects will be distributed in the volume depending on the manufacturing process. Consequently, under axial tensile load, the average failure stress (or strain) will not be deterministic, but will have a probability distribution. Since the average stress in the fibers differs from that in the matrix, we will refer to the average strain in the composite at failure, as this is also the nominal fiber failure strain irrespective of the fiber volume fraction. Thus, let the mean value of the composite failure strain be denoted by ε_c and let the scatter in the failure strain be described by certain convenient extreme values, such as those at 5% and 95% probabilities of failure.

Now let the composite be subjected to an axial tensile load such that the resulting maximum strain, ε_{max}, is within the scatter band of the composite failure strain, as indicated in Figure 1.3, where the maximum applied strain is plotted on the vertical axis. If the composite survives this load, then it can be concluded that none of the fiber failure regions reached the failure condition discussed above and illustrated in the sketch to the right in Figure 1.2. For this condition to occur, sufficiently many fibers must fail in a local region such that the matrix crack formed grows unstably at the maximum applied load. Since the load applied is high enough for the maximum strain to be within the failure scatter band, it is reasonable to assume that many fibers fail in different regions at this load, although the failure condition is not reached in any of those regions. Consider now unloading and reloading to the same maximum load

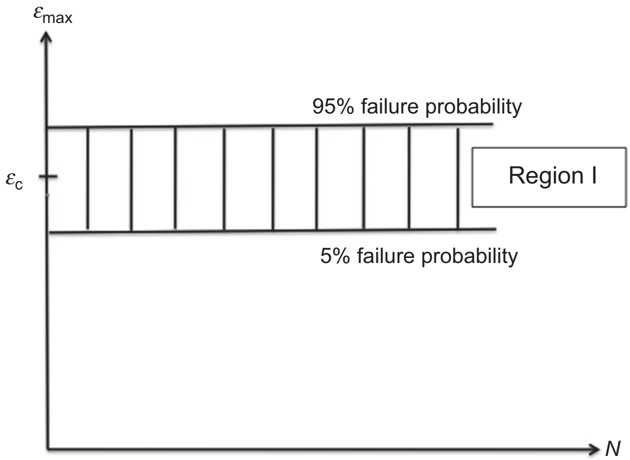

Figure 1.3 Region I of the fatigue life diagram.

value. In the reapplication of load, each of the fiber failure regions will undergo stress redistribution due to the inelastic deformation of the matrix. However, the resulting stress fields in the regions will be different and their consequence in terms of failing more fibers will also be different because of the random distribution of defects (weak points) in the fibers. If the reapplication of the maximum load is repeated, then with each repetition a new scenario of the fiber failure regions will form, with the region most likely to fail the composite in the next application of the maximum load shifting from region to region. Thus, which of the failure regions will reach the composite failure condition first cannot be predicted, as a progressive mechanism that depends on the maximum applied load does not exist. Consequently, the composite failure is not a function of the number of load cycles N and the probability of this failure is also independent of N. In other words, the scatter band of initial failure strain remains unchanged with the number of load cycles N. This is depicted in Figure 1.3. We shall label this scatter band as Region I of the composite fatigue process.

1.3.1.2 Primary role of matrix in composite fatigue

Consider now loading the unidirectional composite in tension such that the maximum strain in the first application of load is significantly below the scatter band of ε_c (see Figure 1.3). Under this load, few if any fibers will be expected to break. However, a real possibility exists that some fibers are broken due to manufacturing, for example, from handling of fibers in dry form or stretching them during impregnation with the matrix polymer. The broken fiber ends are sites of stress concentration in the matrix and, consequently, excursion of the matrix deformation into the inelastic regime. Thus, under repeated load application, these sites will be sources of irreversibility needed to initiate and advance fatigue cracks. The role of fibers now will be to slow down, and possibly arrest, the growth of these fatigue cracks. If the repeating applied load is high enough, then the matrix cracks will grow as fiber-bridged cracks, and the

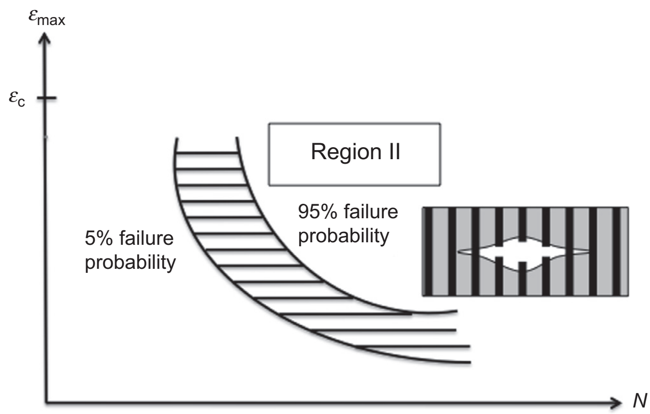

Figure 1.4 Region II of the fatigue life diagram.

crack with the largest cyclic growth rate will reach the composite failure condition. That failure condition can be expressed in energy terms as exceeding the local fracture toughness by the energy release rate of a fiber-bridged matrix crack. It is clear that this criticality condition depends on the size of the crack and the remotely applied load level. As this load level decreases, the crack growth rate reduces, and consequently the number of load repetitions needed to reach the failure condition increases. This trend results in the fatigue life scatter band sloping downwards, as depicted in Figure 1.4, where the fiber-bridged crack is sketched to signify the underlying fatigue mechanism. The scatter band represents the statistical variation caused by the randomness in the crack growth rate as well as in the local fracture toughness at the crack fronts. The fatigue process represented by this scatter band will be called Region II.

1.3.1.3 Fatigue limit

Fatigue limit is not only of interest from a fundamental viewpoint, it is also of practical importance for designing durable structures. The concept of a limiting condition for fatigue, similar to a yield stress for metal plasticity, came from observing that the fatigue life of some metals, particularly steels, was essentially infinite (or much longer than needed for safe performance in most structures) if the maximum stress was kept below a threshold value. This is illustrated in Figure 1.5(a), where the classical $S-N$ plot is sketched, indicating S_0 as the fatigue limit. If the metallic structure develops a crack whose unstable growth defines failure, then the fatigue threshold is expressed in terms of the range of the stress intensity factor, ΔK. That threshold is the value of this quantity below which no crack growth is expected. Figure 1.5(b) schematically plots the crack growth rate (da/dN) against ΔK and indicates the fatigue threshold ΔK_0.

Studies of metal fatigue have indicated that the fatigue limit is sensitive to the microstructure, for example, the grain size, and the mechanisms responsible for limiting fatigue have to do with creating microstructure barriers to the formation of cracks from cyclic slip within grains and, if a crack initiates, to block its advance by such barriers.

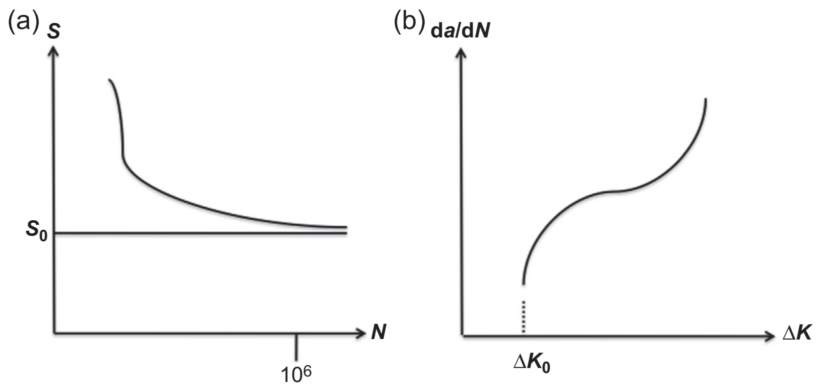

Figure 1.5 (a) A typical stress–life (S–N) plot for metal fatigue, indicating fatigue limit S_0; and (b) a typical crack growth rate versus range of stress intensity factor, indicating the fatigue threshold (ΔK_0).

In a composite undergoing Region II fatigue, the microstructure barriers are the fibers bridging the matrix cracks. These fibers provide resistance to crack growth by reducing the energy release rate (via reducing the crack surface displacement). The fibers ahead of the crack front provide obstacles to the crack growth. In spite of these mechanisms of crack growth retardation, it is likely that the failure condition is not avoided but is reached at very large numbers of load cycles. While in metals 10^6 cycles is viewed as a large number of cycles and is often used to define the fatigue limit, polymer-based composites are used in applications, such as wind turbine blades, where 10^7 or more cycles are expected in the design life. Since testing to such large numbers of cycles is time-consuming and costly, it is desirable that estimates for the fatigue limit can be made from considerations of the mechanisms. An attempt at this follows next.

Figure 1.6 schematically depicts a scenario for arresting the fatigue crack growth in a composite. These cracks are assumed to form by the fatigue process in the matrix polymer under the applied cyclic load. Assuming the applied load level to be low enough that essentially no fibers fail, the matrix polymer surrounding the fibers undergoes cyclic stressing dictated by the cyclic deformation of the fibers. This cyclic deformation produces the same strain in the matrix as in the fibers (and the composite). In order for the matrix to form fatigue cracks, this cyclic strain must be equal to or greater than the fatigue limit of the matrix (measured in terms of strain). Thus, one estimate of the fatigue limit of the composite would be the fatigue limit of the matrix. Obviously, this estimate of the composite fatigue limit ε_{fl} is an approximation, since the local strain in the matrix is assumed to be the same as that in the composite, neglecting any strain enhancement caused by fibers. Thus, the matrix fatigue limit ε_m could be viewed as the lower bound to the composite fatigue limit, that is, $\varepsilon_{fl} < \varepsilon_m$. On the other hand, because of the crack growth arrest by the fibers, depicted in Figure 1.6, the actual composite fatigue limit may be higher than the matrix fatigue limit, that is, $\varepsilon_{fl} > \varepsilon_m$. Fundamental studies are needed to determine how the fiber