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1 Durability assessment of composite structures

1.1 Introduction

Composite structures for mechanical and aerospace applications are designed to retain structural integrity and remain durable for the intended service life. Since the early 1970s important advances have been made in characterizing and modeling the underlying mechanical behavior and developing tools and methodologies for predicting the fracture and fatigue of composite materials. This book provides an exposition of the concepts and analyses related to this area and presents recent results. The next chapters treat damage in composite materials as observed by a variety of techniques, followed by modeling at the micro and macro levels. Fatigue is treated separately because of its particular complexities that require systematic interpretation schemes developed for the purpose. A chapter is added in the beginning to provide convenient access to the mechanics concepts needed for the modeling analyses in later chapters.

Here we present an overview of the durability assessment process for composite structures. Figure 1.1 depicts the connectivity and flow of the elements of this process. To begin, one usually conducts stress analysis of the component using the "initial" constitutive behavior of the composite along with the service loading on the component as input. In contrast to monolithic materials, such as metals, the constitutive behavior of a composite can change due to damage incurred in service. The stress analysis combined with prior experience allows identifying critical sites ("hot spots") in the component that are prone to be the sites of failure. Further examination of these sites in terms of the local stress/strain/temperature excursions combined with the composite material composition at those sites helps to identify the possible mechanisms of damage that can result. Examples of such mechanisms are microcracking of the matrix, delamination (separation of layers at interfaces), aging (of the polymer matrix), etc. Chapter 3 describes these mechanisms in some detail. The next step is to analyze the consequences of the mechanisms on the material response and in turn on the structural performance. Chapters 4 and 5 deal with different models to predict the damage-induced material response changes. Since the scales at which damage occurs are small in comparison to the characteristic geometrical size of the "hot spots," models must account for the multiple length (or size) scales. The differentiation of scales is conventionally described as "micro" (the scale of damage) and

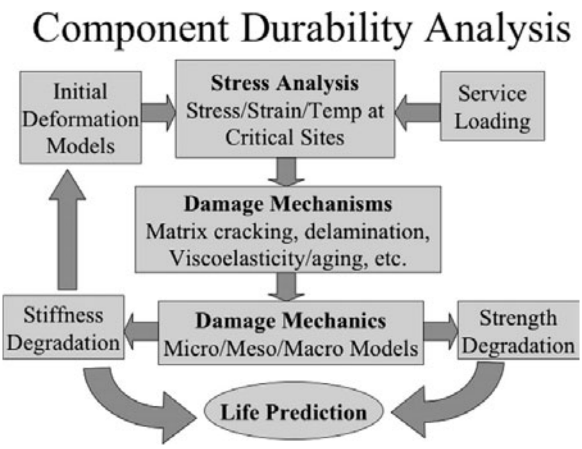

Figure 1.1. A durability analysis scheme for composite structural components.

"macro" (the scale at which structural response is characterized). Since connectivity between these scales must be established, an intermediate scale called "meso" is defined as needed by the particular model used. In micromechanics the concept of "representative volume element" (RVE) has been proposed. The size of this element is commonly taken to be the meso scale. Chapters 4 and 5 describe the three scales in the context of different models. Chapter 6 is focused on the initiation and progression of damage. Together the three chapters provide the content of the subject known as "damage mechanics," which as indicated in Figure 1.1 is central to durability assessment.

The common output of the damage mechanics models is a description of the material response, often described as "stiffness degradation," caused by damage. This description necessarily involves averaging over the so-called RVE. Thus the materials response, or averaged constitutive behavior description, forms the new input to the stress analysis that was conducted initially using pristine (undamaged) material properties. The resulting iterative process of stress analysis should be an inherent feature of composite structural analysis, although the industry practice currently does not fully implement this procedure. Another output of the damage mechanics analysis is "strength degradation," i.e., reduction in the load-bearing capability of the structure due to damage. Depending on the functional requirements of a given structure, degradation of stiffness or strength would be the path to loss of structural integrity. A typical example of a stiffness-critical structure is an aircraft wing that must deform appropriately to perform its aerodynamic function, while a fuselage is strength-critical as its design requirement is to contain the pressure within it.

While monolithic materials such as metals fail due to unstable growth of a crack, the heterogeneous internal structure of a composite leads to formation of multiple cracks. A generic heterogeneous solid is illustrated in Figure 1.2 in three states: pristine (undamaged) to the left in the figure shows a representative region

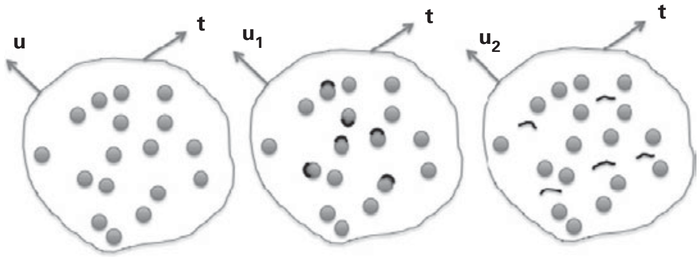

Figure 1.2. A heterogeneous solid in pristine (undamaged) state (left) and in two possible multiple cracking states (middle and right).

of the solid within which heterogeneities (reinforcements) are indicated symbolically as filled circles, and two states that have multiple cracks resulting from debonding of reinforcements (middle figure) and from local failure of the matrix induced by defects and/or stress concentrations. Consider the external loading on a composite structure resulting in tractions **t** on the surface bounding the representative region of the composite shown. If the response to these tractions in terms of the bounding surface displacements is given by **u** in the pristine state, then the surface displacements of the multiple cracks (commonly expressed as crack opening displacements, COD, and crack sliding displacement, CSD) within the volume will change this to $\mathbf{u_1}$ or $\mathbf{u_2}$ depending on the type of damage (see Figure 1.2). The local environment around the cracks influences the COD and CSD of distributed cracks within the volume. This local environment is typically described as a "constraint" (i.e., moderation) to the crack surface displacements and is expressed in terms of the variables of heterogeneities. If the heterogeneous solid with multiple cracks is homogenized over the representative region, then the stress–strain response averaged over the RVE is given by the averaged stiffness properties that change (degrade) with increasing number of cracks and the constraint to the crack surface displacements. This stiffness degradation is the subject of damage mechanics, as discussed above in describing the durability assessment procedure depicted in Figure 1.1.

1.2 Historical development of damage mechanics of composites

Although the field of solid mechanics applied to heterogeneous solids was developed in the late 1950s and early 1960s, and became known as micromechanics, the specific situations encountered in composite materials such as those with continuous fiber reinforcements were not addressed until much later. The concepts developed in micromechanics turned out to be useful for multiple cracking in composite materials and are recommended as essential background (see the text by Nemat-Nasser and Hori [1]). However, the first pioneering work that clarified the phenomenon of multiple cracking in the presence of fiber/matrix interfaces in reinforced composites was by Aveston *et al*. [2] published as a conference proceedings paper in 1971.

This work, which became known as the ACK theory, treated multiple parallel cracks normal to fibers in a matrix with all fibers in one direction loaded in tension along fibers. The model produced an expression for the overall strain at which multiple cracking occurs based on a simplified stress analysis and energy balance concepts. The expression provided a basis for assessing the roles of fiber and matrix properties, their volume fractions, and the fiber diameter in resisting multiple cracking.

The ACK model was motivated by the observation of multiple cracking in brittle matrix composites such as cement reinforced with steel wires. For polymer matrix composites, the application of the ACK theory was at first not clear since a ply with unidirectional fibers of glass or carbon does not have the right conditions for multiple cracking when loaded in tension along fibers. Garrett and Bailey in 1977 [3] found that the multiple cracking observed in cross-ply laminates of glass fiber-reinforced polyester under axial tension could in fact be described well by the case of fully bonded interfaces treated by Aveston and Kelly [4] in a follow on paper to the ACK model. This required replacing the matrix and fibers in that model by the transverse and longitudinal plies, respectively. Garrett and Bailey then repeated with appropriate modification the one-dimensional stress analysis and energy balance considerations used in [4]. Thus began a long series of works that applied the one-dimensional stress analysis, known as shear lag analysis, which assumes axial load transfer from cracked to uncracked plies by the shear stress at the interfaces.

The inadequacy of the shear lag analysis to properly provide stresses in the cracked cross-ply laminate was a severe limitation until a variational analysis-based two-dimensional approximation appeared in the English literature [5]. This spurred further work of more accuracy [6] and extension to partially debonded frictional interfaces [7], while extension to cracked plies of other than transverse orientation required other approaches [8]. The analyses that use local ply stress solutions to evaluate overall stiffness degradation are grouped together in "micro-damage mechanics" (MIDM) and are treated in Chapter 4.

In some ways parallel to the MIDM emerged another approach that became known as continuum damage mechanics (CDM). Its beginnings are not attributed to composite materials but to metals undergoing creep. Kachanov in 1958 [9] put forth a concept of a field of internal material discontinuity responsible for distributed local stress enhancement leading to overall creep strain. Later, the internal state was called damage and a (hidden) scalar variable D was associated with it. The continuum now had an internal damage state and because of its irreversible nature its treatment required thermodynamics, in particular the Second Law, which places conditions on the entropy changes. Kachanov's work stayed relatively unknown until Lemaitre and Chaboche [10] applied it to analysis of various structural materials with distributed cavities and cracks. Krajcinovic [11] further enhanced the field by connecting it to concepts known from fracture mechanics and plasticity and by elaborating the thermodynamics implications. For composite materials of technological interests that are constructed with specific symmetries such as orthotropic, the first work to apply CDM was by Talreja [12] and its companion paper that

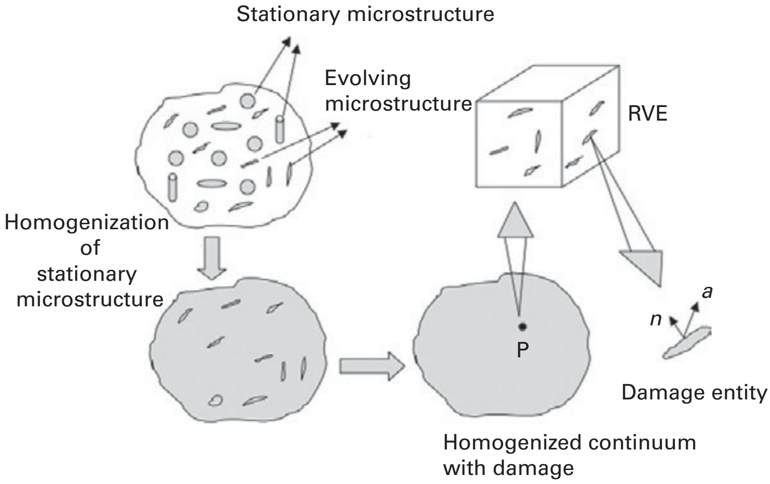

Figure 1.3. Illustration of the CDM concept for composites.

validated the stiffness degradation relationships by experimental data [13]. The CDM concept for composites is illustrated in Figure 1.3. The reinforcements in a composite are regarded as a stationary microstructure and are homogenized as an anisotropic medium in which the damage entities such as cracks are embedded. Further homogenization is done by smearing out the damage entities into an internal field, which is represented by a pair of vectors, whose dyadic product averaged over all damage entities in a RVE provides the characterization of damage. Since the early papers [12, 13] the CDM field for composite materials has developed steadily, more recently in a version named as synergistic damage mechanics (SDM) where the micromechanics is judiciously applied to enhance the applicability of CDM. All this is the subject of Chapter 5 on macro-damage mechanics (MADM).

As depicted in Figure 1.1, the stress analysis of critical structural sites requires stress–strain relationships that reflect the presence of damage. These relationships are developed by combining stiffness degradation and damage evolution. The subject of damage evolution is complex with its own challenges. Therefore Chapter 6 is devoted exclusively to its treatment.

1.3 Fatigue of composite materials

It is natural to assume that the complexities of damage in composite materials observed under quasi-static loading would be enhanced when the loading is applied in a cyclic manner. The experience with metal fatigue indicates that the fracture surface of a sample failed in fatigue shows distinctly different features than if failed in the application of a monotonically increasing load. The fracture surface of a unidirectional fiber-reinforced composite loaded along fibers monotonically or cyclically does not give clear indication of mechanisms preceding failure in either case. In more general fiber architectures, such as laminates and woven fabric composites, following the events from the first (initiation) to the last (separation by breakage) is generally difficult. However, as advances in nondestructive observation techniques are made, increasing clarity in mechanisms is emerging. In the early years of composite fatigue studies in the 1970s, little was understood of mechanisms and consequently the assumptions made in predictive models were speculative at best.

One study of a unidirectional glass/epoxy composite made assumptions of fatigue mechanisms that led to reasonable explanation of the trends in fatigue life [14]. Following that work, a systematic conceptual framework for interpretation of fatigue damage and failure was proposed by Talreja [15] for more general cases of loading as well as for more general fiber orientations. The framework took the form of a two-dimensional plot called a "fatigue life diagram" in which regions of dominant mechanisms were separated. The diagram is not meant to be a data-fitted S-N curve (historically known as a Wöhler diagram) but as a means of interpreting the roles of fibers, matrix, and interfaces as well as of laminate configuration parameters such as ply orientation, sequence, and thickness.

Since the unidirectional composite (or ply) is a basic unit in laminates, the fatigue life diagram for this composite under tension–tension loading forms the baseline diagram from which more general cases evolve. This diagram is illustrated in Figure 1.4 and discussed in detail in Chapter 7. As shown, the vertical axis of the diagram is the maximum strain attained at the first application of maximum stress in a load controlled fatigue test. This quantity forms a proper reference to the loading condition and provides upper and lower limits to the fatigue behavior. Thus the strain to failure (of fiber) forms the upper limit while the strain corresponding to the fatigue limit (primarily a matrix property) forms the lower limit. These strain values can always be converted to applied stress, but plotting these in the diagram allows a systematic and proper interpretation of the roles of the constituents. The regions indicated in the fatigue life diagram provide clarity of the governing mechanisms dictated by the constituent properties. The construction of the diagram for unidirectional composites was initially based on systematic arguments and logical deduction. Physical evidence to support the diagram was later presented by an elaborate and tedious experimental study [16].

The fatigue life diagram can also serve the purpose of facilitating mechanisms-based life prediction modeling. For cross-ply laminate this was demonstrated in [17]. Generally the path to predictive modeling with account of the underlying damage mechanisms is long and hard. Consequently, the literature has a preponderance of studies that resort to "failure criteria" that are mostly extensions of those for static failure with assumed procedures without fundamental validation. The models are therefore not reliable enough to extend beyond the cases that formed the impetus for the proposed schemes.

Chapter 7 treats the subject of composite damage with emphasis on mechanisms. It is not exhaustive in the sense of including the literature on models for life

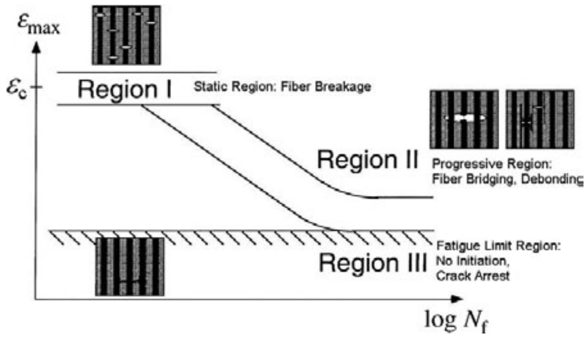

Figure 1.4. Fatigue life diagram of a unidirectional fiber-reinforced composite subjected to cyclic tension in the fiber direction.

prediction. A recent paper [18] has a fairly thorough examination of the main models for multiaxial fatigue. It reveals the frustrating situation of lack of reliability of the models. In Chapter 7 the main findings of this review are discussed and a mechanisms-based methodology is proposed.

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2 Review of mechanics of composite materials

In this chapter the fundamental aspects of elasticity, strength, and fracture of composite solids are reviewed. Although this information is available in numerous texts, more comprehensively and in greater detail than here, a brief exposition is provided for convenient reference. For further in-depth treatment, the reader may consult, e.g., [1–5] for theory of elasticity and continuum mechanics, [6–12] for mechanics of composite materials, and [13–17] for fracture mechanics.

2.1 Equations of elasticity

2.1.1 Strain–displacement relations

Figure 2.1 illustrates the initial and deformed configurations of a body whose representative material point P is described with respect to a fixed rectangular Cartesian frame by coordinates X_j and x_i respectively, $j, i = 1, 2, 3$. The components of displacement of the point are given by

$$u_i = x_i - X_j \delta_{ij}, \tag{2.1}$$

where X_j are the coordinates of the material point in the initial undeformed configuration, x_i are the coordinates of the material point in the final deformed configuration, and δ_{ij} is the Kronecker delta. The Lagrangian description of displacement at time t is expressed in terms of the X_j coordinates as

$$u_i = x_i(X_1, X_2, X_3, t) - X_j \delta_{ij} \,. \tag{2.2}$$

The components of the Green–Lagrange strain tensor are given by

$$E_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i} + u_{i,k}u_{j,k}\right), \tag{2.3}$$

where $u_{i,j} = \dfrac{\partial u_i}{\partial X_j}$, etc., and repeated indices imply summation.

When $\left|u_{i,j}\right| \ll 1$, E_{ij} reduces to the infinitesimal strain tensor ε_{ij} given by

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \equiv \frac{1}{2}\left(u_{i,j} + u_{j,i}\right). \tag{2.4}$$

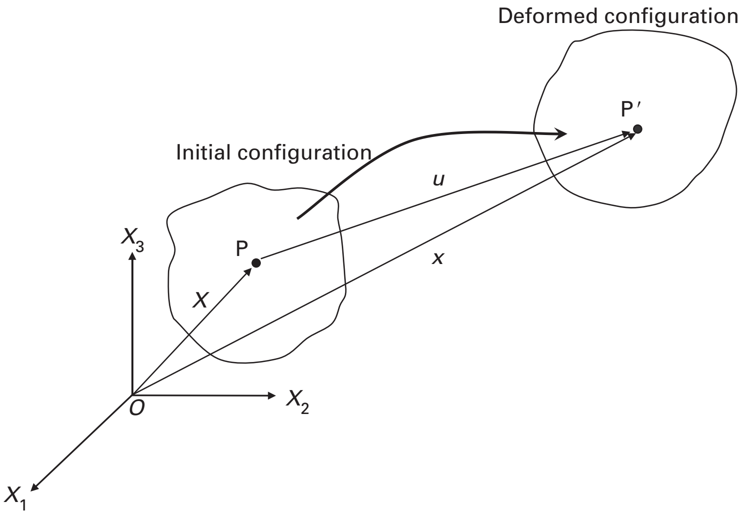

Figure 2.1. Initial and deformed geometry of a continuum body.

From Eq. (2.4) it is seen that the strain tensor is symmetric. Thus, there are six independent strain components, which in the infinitesimal version are three normal strains (ε_{11}, ε_{22}, and ε_{33}), and three shear strains ($\varepsilon_{12} = \varepsilon_{21}$, $\varepsilon_{23} = \varepsilon_{32}$, and $\varepsilon_{13} = \varepsilon_{31}$).

To ensure single-valued displacements u_i, the strain components ε_{ij} cannot be assigned arbitrarily but must satisfy certain integrability or compatibility conditions, given by

$$\varepsilon_{ij,kl} + \varepsilon_{kl,ij} - \varepsilon_{ik,jl} - \varepsilon_{jl,ik} = 0. \tag{2.5}$$

Of the 81 equations included in Eq. (2.5), only six are independent. The remainder are either identities or repetitions due to symmetry of ε_{ij}. For the special case of plane stress conditions, the only surviving compatibility equation is

$$\varepsilon_{11,22} + \varepsilon_{22,11} - 2\varepsilon_{12,12} = 0. \tag{2.6}$$

2.1.2 Conservation of linear and angular momenta

In general, the forces exerted on a continuum body are body forces and surface forces. Body forces, such as gravitational and magnetic forces, act on all particles within the volume of the body and are described in terms of force intensity per unit mass or per unit volume, while surface forces are contact forces that act across an internal surface or an external (bounding) surface. The continuum description of surface forces is given by the traction vector **t** acting on a surface element dS with a unit normal **n** (see Figure 2.2(a)). Let d**P** be the total force exerted on dS by the material points on the side of dS toward which **n** is pointing. The traction vector ***t*** is then defined as

$$\mathbf{t} = \lim_{\mathrm{d}S \to 0} \frac{\mathrm{d}\mathbf{P}}{\mathrm{d}S}. \tag{2.7}$$

At an internal point P there are infinitely many surface elements, each with a different unit normal vector. According to the Cauchy theorem a traction vector on any of these