Modeling of Damage Evaluation and Failure of Laminated Composite Materials

J. Joy Mathavan, Muhammad Hafiz Hassan, and Gérald Franz

1 Introduction

Due to the anisotropy and heterogeneity of fiber-reinforced composite materials, the growth of damage in the composite materials is a complicated process. In contrast to metallic materials, damage to fiber-reinforced composites under static or cyclic loading situations [1] with very large amplitudes is dispersed rather than confined [2]. The damage-accumulation process, which is associated with the beginning and progression of a damage, frequently causes composite materials to lose some of their elastic properties, known as stiffness degradation. In reality, the change in stiffness during the fatigue life of a fibre composite material caused by change in residual strength is normally lesser than the degradation [3]. Additionally, since the development of microdefects always occurs before the formation of macrocracks, the spread of a single macrocrack in the structure does not always cause for the failure in a composite [4]. Various microdamage mechanisms begun based on the level of anisotropy, inhomogeneity, and the loading conditions used. They can manifest and grow individually or in combination, resulting in a range of situations for the failure of composite materials or for the degradation of their properties [5]. Additionally, the causes of failure of composite materials and degradation of properties are dependent

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on the scaling factors of the composite structure. As a result, multiscale modelling of the damage accumulation process in relation to the deterioration of the property is required [6, 7].

2 Microdefect Mechanisms in Fiber-Reinforced Composites

In this part, the outline of several common microdefect mechanisms that occur during the formation and accumulation of microdefects in fiber-reinforced composite laminates will be discovered. Instead of providing a detailed analysis of the damage-accumulation procedure that directs to the failure of microdamage mechanisms at the ply and constituent scales of fibre reinforced composite materials subjected to variance of loading, the goal here is to highlight the distinct and key damage mechanisms that causes the degradation of properties in composite materials [8, 9].

2.1 Typical Microdefect Mechanisms

During manufacturing, some microdefects, called “built-in defects,” are easy to see. These include broken fibres, volumetric voids in the matrix, misaligned fibres, and disbonds at fibre matrix interfaces. Disbonds are areas where the fibres and matrix no longer stick together. Although these mechanisms are quite tiny and thus unlikely to cause the composite to fail entirely, they can gradually deteriorate its effective qualities. Similarly, voids in composite materials can impair their mechanical qualities [10]. When initial loads are applied to composites, these broken fibres, voids and disbonds can also operate as stress risers, collecting and/or triggering additional microdamage environments. As a result, these degradation processes can have a vital effect on the failure of fibre composite materials and deformation behavior depending on their size, shape, and distribution [11].

Since composites aren’t uniform, damage starts to spread or change in fiber-reinforced composite materials early in the loading process, which includes mismatched fibre, matrix, and interface properties. Anisotropy (which includes the directional properties of fibres and the orientation of a fibre in the laminate) and matrices such as transversely isotropic and isotropic are also some causes for damage propagation early in the loading process. Because of these properties of composites, whenever external loads are applied, significant inhomogeneous stress and strain fields arise. Stress inhomogeneity is exacerbated further in composites by geometric-scale structural characteristics namely ply thickness, fibre volume fraction, layup number and localized fibre packing and spacing [12]. In addition, the stress inhomogeneity of composites may be exacerbated by inherent flaws [13]. Thus, some micro-volumes in the composite are likely to experience higher levels of localized stress than others, which can lead to a variety of damage, including new types of damage, and the expansion of existing damage, if the higher localized stresses exceed their respective strength limits at an early loading stage. This damage-accumulation process results in a rise in stress redistribution and stress inhomogeneity in the composite, as a result of the increasing size and presence of microdefects, which are the consequence of the increased number of loading cycles in fatigue loading or increased load in quasistatic loading [9, 13]. In return, when the number of loading cycles or size of the load increases, the effective characteristics of a fibre composite material change or decrease. Some micro damages may reach saturation points in the middle and end stages of loading or combined, resulting in the formation of further microdamage mechanisms and the appearance of macrocracks, which may ultimately result in the failure of the fibre reinforced composite material [14]. Our primary focus is on the microdamage mechanisms that start and develop during the initial and intermediate loading steps for composite materials (see Fig. 1).

Apart from the inhomogeneity and anisotropy of a composite, microdamage mechanisms are triggered by the loading circumstances that were used on the composite material. Individual fibres fail at their weakest points when a unidirectional fibre reinforced composite is exposed to quasistatic or cyclic tensile loading along the fibres because the fibres carry practically all of the load. These weak areas may be defined by built-in problems within and adjacent to the fibers or by flaws in the fiber architecture. Fiber breaking is the predominant mechanism of fracture during the initial loading process since it regulates the growth and accumulation of local microdamage leading to the composite's ultimate failure. This is because when a fiber breaks, it perturbs the local tension in its surroundings, resulting in stress rearrangement between the fibers and the matrix. Zero stress exists where the fibre breaks, and some distance away from the break is referred to as an ineffective length when

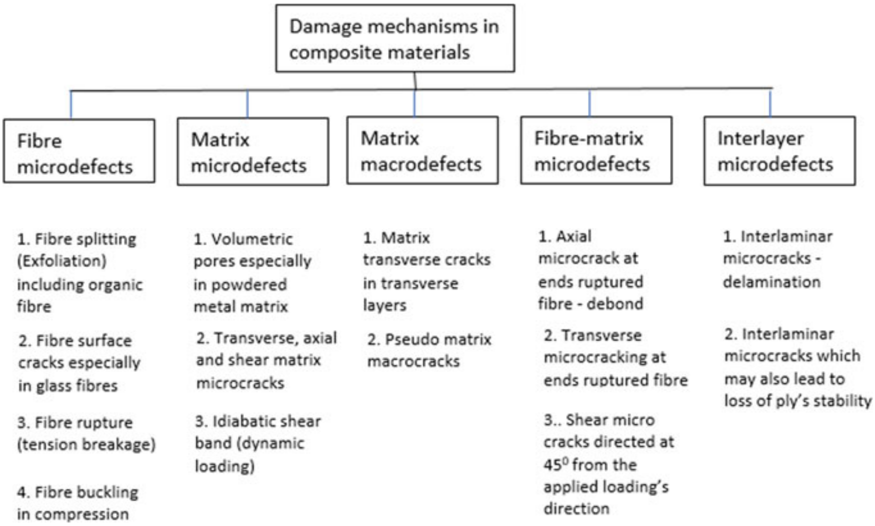

Fig. 1 Classification of microdefects in composite materials and a few significant microdefects

tension is progressively recovered. The fibre matrix interface and matrix also redistribute stress to neighboring fibres, creating an area of elevated stress concentrated near broken fibres and causing further fibre breakage provided that the strength limit of the fiber is exceeded. Additionally, this area of high concentration is expected to induce extra microdamage mechanisms in the matrix and at the interface [15]. These mechanisms include longitudinal microcracks (cracks along the fiber) and transverse microcracks (cracks to the fiber). A transverse microcrack in the matrix may grow to reach neighboring fibres when it begins at the ends of shattered fibres and spreads outward [15]. From the ends of fractured fibers, a transverse microcrack in the matrix might expand to reach adjoining fibers. If the break spreads over nearby fibres, a fiber-bridge crack is thought to form at this point. Additionally, the fracture may be stopped at the intersections of nearby fibres that are still intact, leading to the formation of longitudinal microcracks. A longitudinal microcrack that is started by a broken fibre might spread in the matrix or at the fiber-matrix interface, a process called as debonding. Damage progression situations are dependent on interfacial adhesion strength, underscoring the interface's critical involvement in the microdamage mechanisms of the fiber reinforced composite materials. If the interface is robust, transverse matrix microcracks will develop and spread, whereas longitudinal or axial matrix microcracks will form and grow if the interface is relatively weak [13].

For multidirectional laminates exposed to fatigue tensile and quasistatic loading circumstances, the longitudinal or axial plies continue to be crucial structural components that withstand applied loads and retain the functionality of the composite structure. The laminate's symmetric off-axis and transverse plies, as well as the order in which these plies are stacked, can have a big impact on how well the longitudinal layers of the composite perform; that is, the rate at which microdamage mechanisms initiate and accumulate on off-axis and transverse plies which can affect the inhomogeneous stress distributions of longitudinal layers adversely, and thus influence the performance. Assume quasistatic tensile or fatigue loading causes normal damage to cross-ply laminates. Disbonds and matrix microcracks in transverse plies might occur during initial loading. Debonding microdamage is more common in transverse plies due to the greater strength of the fiber and matrix compared to the interface. Stress risers are formed by unbroken fibers near disbonds, and matrix microcracks begin to emerge because of continued loading. These disbonds merge to generate cracks that cross the transverse ply's thickness. Plies can develop a succession of numerous transverse-ply cracks in their respective orientations. When transverse-ply fractures emerges, high concentration zones are formed between axial and transverse plies, which may lead to delamination or interlaminar cracking, commonly known as ply-separation microdamage [16, 17]. When fiber reinforced composites are subjected to tensile, tension, compression fatigue stress and compressive loading, delamination can have a significant impact on their performance and integrity. It is also possible for composite structures to delaminate at the margins [18]. Although microcracks begin at a higher applied axial strain in off-axis plies than in transverse plies, damage evolution is similar as like in quasi-isotropic laminates when off-axis plies are present in the laminate. Off-axis plies can also develop curved or oblique microcracks. There are several factors that can affect the onset of and accumulation of microcracks in composite materials, which can have a substantial impact on their properties and failure [19].

It is well acknowledged that fiber micro buckling/kink-band development is the primary cause of longitudinal plies failure under compressive quasistatic and fatigue loads. When a composite is loaded more and more, the fibers shatter at two locations, an event that is frequently triggered by inherent faults such as misalignment of fiber. The kinking process then happens abruptly, which may result in the fiber composite material failing catastrophically. The transfer of stress around the damaged fibre results in the creation of other types of defects. With increased loading, disbonds at the fiber-matrix interfaces, microcracks in the matrix, and delamination between plies may appear. In order to prevent catastrophic failure of fibre composite materials subjected to compressive pressure, interactions between various damage mechanisms are essential. It has been hypothesized that ply splitting, instead of fibre micro buckling, causes kink-band formation, but because of the brief period of the kinking process, the actual mechanism which causes kink-band development is still remain as a question [4, 19]. At the very least at the microscopic level, and predominantly at the constituent level, it is yet unknown how microdamage mechanisms that directs to catastrophic failure emerge, evolve, and interact. This holds true for laminates that are both multidirectional and unidirectional and that are subjected to quasistatic, fatigue compressive, tensile, compressive and multiaxial fatigue loading conditions. However, these stress circumstances are highly destructive to fiber reinforced composite materials, and it is not fully understood how their underlying microdamage mechanisms originate and accumulate, specifically at the constituent level. Based on published data, the numerous significant microdefect classifications, as well as a few significant microdefect classifications, that have been identified in composite materials under a variety of loading circumstances was proposed [20].

2.2 Micromechanical Model of the Composite Materials Degradation Process

As previously stated, it is a significant task to predict the damage accumulation process and stiffness deterioration when a variety of factors may have impact on numerous leading damage mechanisms that begin and develop in fibre reinforced composite materials. The majority of industrial researchers and practitioners have opted for an empirical method due to this complexity and difficulties. Although this approach is useful since it uses an empirical mathematical model that has been fitted to real data, it can be rather expensive given the number of experimental programs. Beyond the confines of experimental restrictions, prediction capacity could also be limited. On the other hand, if the underlying physical mechanisms of the composite damage-accumulation procedure are understood, a more tenable mechanism-based approach offers stronger prediction power [21, 22]. It is challenging, as previously said, to address all physical causes, especially given the vast array of composite material characteristics, such as stacking sequences, constituent quality, ply directions and other intricate designs and geometries. Instead, one may concentrate on the underlying damage mechanisms that control damage processes when particular loading conditions are applied to composite structures, create their connections with continuum micromechanical models and then improve the models using empirical data [23, 24].

3 Modelling Microdefect Evaluation and Failure in Composite Material Lamina

3.1 Characteristic of Microdefect in Kinetic Model

Microparameter s_i can be used to describe some of the properties of microdefects. Matrix delamination (debonding) from fiber, microcrack length or area, volume of micropores and length or squared length of a crack between layers are all examples of this characteristic. This microparameter can be more accurately described by the relationship between the stress intensity at the fracture tip and the actual stress value in a lamina.

Measures of microparameters s_i are introduced for different sorts of microdefects. These may be scalars, vectors, or tensors. There are several vectors that can be used to describe flat microdefects; for example, a vector that is identical in length, in magnitude and in direction to a normal vector that is defined in the specific coordinate system of a composite construction. Microdefects are often measured using a scalar scale. Another property of these microparameters is that they should not change with the translation of a coordinate system that denotes linear elements of space–time s_i. A mathematical operation like summing, subtraction, or multiplication will yield the identical values irrespective of the coordinate system employed to measure these parameters [25, 26].

3.2 Kinetic Damage Model

A general damage characteristic S will be established, which will be outlined as the total number of microdefects s_i available in the representative volume element at a particular time in the damage process. Additionally, we will investigate how property degradation is affected by this damage value. The value s varies during the loading process for various sorts of microdefects and it depends on the process parameter t as well as the parameter value t_0, which represents the moment the microcrack started. As a result,

$$s = s(t, t_0) \tag{1}$$

The value v that represents the birth rate of microdefects indicates the birth (beginning) of microdefects in the current representative volume of a material (t, S). Say the number of microcracks in a lamina is N. We apply the following formula to determine the quantity of microdefects started during the brief time span dt 0:

$$dN = v(t_o, S)dt_o \tag{2}$$

Equations (1) and (2) can be used to calculate the total damage based on the quantity of microdefects that were initiated between the times dt_0 and t:

$$dS(t, t_0) = s(t, t_0)v(t, S)dt_o \tag{3}$$

Consequently, the measurement of damage brought on by the appearance of microdefects at various intervals can be expressed as:

$$S = \int_0^t s(t, t_0)v(t_0, S)dt_o \tag{4}$$

Here, the Volterra integral evolution equation is satisfied by the parameter S presented in Eq. (4), which defines the overall state of damage. Next, we will use the following differential function to define the growth or development process of microdefects:

$$\frac{ds}{dt} = f(t, s, S) \tag{5}$$

Combining Eqs. (3) and (4), we have

$$\frac{dS}{dt} = s(t, t)v(t, S) + \int_0^t f(t, s(t, t_0)v(S, t_0)dt_o \tag{6}$$

After that, we will use the first two terms of the small-parameter Taylor expansion to extend the function f(t, s, S) in Eq. (4). Lastly, using Eqs. (3), (5), and (6), we get the set of kinetic equations below, which describes the entire damage buildup process:

$$\frac{dN}{dt} = v(t, S); \quad \frac{ds}{dt} \approx a(t, S) + b(t, S) \tag{7}$$

$$\frac{dS}{dt} \approx s_0 v(t, S) + b(t, S)S + a(t, S)N \tag{8}$$

Here, the scalar microparameters a(t, S) and b(t, S) are associated with the development of microdefects. Lastly, the beginning conditions listed below must be met by the system of kinetic equations presented in Eq. (7):

$$S|_{t=0} = S_{0,} \quad s|_{t=0} = s_{0,} \quad v|_{t=0} = v_{0,} \tag{9}$$

The system of kinetic equations produced can be expanded to include situations in which tensor parameters serve to describe both local microdefects and overall damage.

3.3 Damage Evaluation and Failure Process in Lamina

The current work thoroughly examines the delamination propagation, failure behaviors and buckling response of a simplified multi-layered fiber reinforced composite laminate with a centrally inserted circular delamination [25, 27]. The laminate is rectangular and has the dimensions L × B × H, as shown in Fig. 2a. The laminate is tested for uniaxial compression force exerted in the x-direction. Only the out-of-plane displacements of the unloaded edges are supported and the loading edges are clamped. The Base-laminate, which is a portion of the entire laminate except for the delaminated area (which is an orifice plate), the Upper sub-laminate, which is in the delamination area and over the delamination location, and the Lower sub-laminate, which is in the delamination area and under the delamination location, are the three components of the delamination boundary and position, as shown in Fig. 2b.

According to the theory of brittle fracture mechanics, once the energy release rate at the delamination tip has surpassed a critical threshold, which is $G > G_C$, the delamination will spread. Regarding the current problem under investigation, the

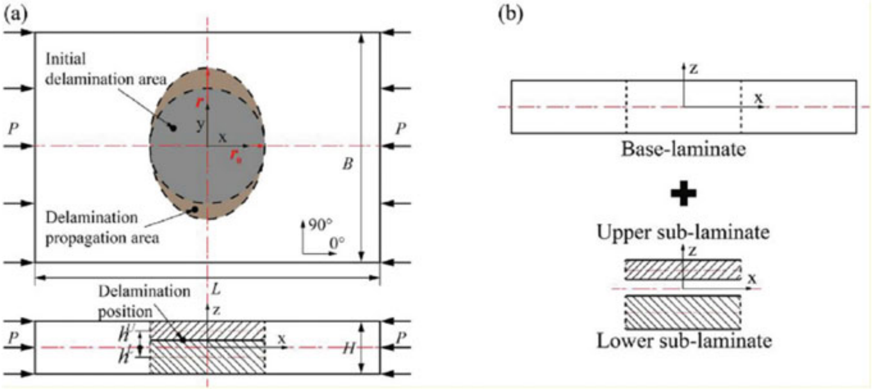

Fig. 2 A composite laminate with an embedded delamination as modelled geometrically and mathematically [28]

energy release can be stated as the partial differentiation of the total potential energy of the structure with regard to the delamination area (A), as shown below:

$$G = \frac{\partial \pi}{\partial A} \tag{10}$$

The boundary conditions and delamination are symmetric about both the x and y axes when the problem under investigation is taken into account. Butler et al. [29] claimed that the delamination has an elliptical form and may be expected to spread only on transverse direction to the compression applied and in our case this is along the y-axis. The dimension parameter r (which is constant before the spread of the delamination i.e., r_0) can then be used to calculate the area of the propagation of delamination, as shown in Fig. 2a:

$$A = \pi r_0 r \tag{11}$$

Then the continuously spreading delamination boundary shape function $f^D(x, y)$ in Fig. 2 can be given as:

$$f^D(x, y) = \frac{x^2}{r_o^2} + \frac{y^2}{r^2} - 1 \tag{12}$$

The energy release rate at the transverse delamination tips can be calculated by substituting Eq. (11) into Eq. (10), and the following criteria can be obtained to determine the delamination growth in that particular direction:

$$G = -\frac{1}{\pi r_0}\frac{\partial \pi}{\partial r} \geq G_C \tag{13}$$

Another important consideration is the selection of G_C, which can directly influence how conservative the results were. According to the Benzeggagh-Kenane law, the main mixed-mode state in which delamination propagates is one where there is an opening mode, shearing mode and tearing mode. In addition, as shown in Eq. (13), the critical energy release rate Gc must satisfy the formula $G_{IC} < G_C < G_{IIC}$ where G_{IC}, G_{IIC}, and G_{IIIC} are the critical energy release rate components for the three delamination modes, respectively and y is a parameter that has been experimentally fitted to the material. The analytical model discussed above, however, does not allow for the precise determination of Ge and the mixing ratio. Obviously, if $G = G_{IC}$ is assumed, a conservative solution can be found. However, the out-of-plane deflection, which is directly connected to the opening mode, is rather minor for a laminate with limitations on the unloaded edges, and the delamination would primarily occur under a shearing or tearing mode in this scenario. As a result, the critical energy release rate is set at $G = G_{IC}$, which is more in line with the actual circumstances of this problem. The impact of G on the outcomes will be covered in the following section. Here G_I, G_{II}, and G_{III} are the energy release rate components.

$$\begin{cases} G_{\mathrm{IC}} + (G_{\mathrm{IIC}} - G_{\mathrm{IC}})\left(\frac{G_{\mathrm{II}}}{G_{\mathrm{I}}+G_{\mathrm{II}}}\right)^n = G_{\mathrm{C}} \\ G_{\mathrm{IC}} + (G_{\mathrm{IIC}} - G_{\mathrm{IC}})\left(\frac{G_{\mathrm{II}}}{G_{\mathrm{I}}+G_{\mathrm{II}}+G_{\mathrm{III}}}\right)^n = G_{\mathrm{C}} \end{cases} \tag{14}$$

Additionally, it is found that, for a particular deformation condition, the external force would decrease as the delamination spread farther. The laminate in this work fails when Eq. (15) is satisfied as advised in engineering practice, which occurs after the force has decreased by more than 4.10%. At that point, the calculating process is completed.

$$\frac{\Delta P}{P_{\max}} < -4.10\% \tag{15}$$

Equation (15) offers a way for predicting the residual strength of a delaminated laminate for a specific G_{C}. Furthermore, taking into account the selection of G_{C} inside $G_{\mathrm{IC}} \leq G_{\mathrm{C}} \leq G_{\mathrm{IIC}}$ in Eq. (13), the proposed model can then be used to determine a specific failure load range.

$$P_I \leq P_{\max} \leq P_{\mathrm{II}} \tag{16}$$

4 Conclusion

The damage development and degradation models presented in this chapter use a micromechanical empirical approach. The formation and degradation of micro defects during the intermediate and final phases of damage development in fiber-reinforced composite materials is the main focus of many authors' works, despite the fact that numerous similar models for describing damage progression in composite materials have been produced. The early and intermediate phases of the damage development process, which are the main subject of the chapter, serve as the framework for the suggested model. As a result, both the micro defect beginning and propagation processes in fiber reinforced composite materials are included in the damage growth and stiffness degradation models. Additionally, the recommended models are strong enough to account for the variety of micro flaws that are generally acknowledged as the main damage processes in charge of deteriorating the useful properties of fibre reinforced composite materials under varied loading conditions.

As previously stated, because of the anisotropy and heterogeneity of fiber-reinforced composite materials, damage evolution is a highly complicated process. However, modeling and predicting the damage-growth process and its effect on the effective properties of fiber reinforced composites can be simplified by identifying the most likely damaging mechanisms which can cause stiffness degradation. Additionally, using microdamage accumulation and degradation models (for a single ply or multiple plies) which are expected to result stiffness degradation in the laminate structure of composite materials, it is simple to assess the degradation of properties that may establish the fatigue limit of any composite material structure, such as stacking sequence and ply orientation. Though, an empirical model is considered to assure the results' trustworthiness and accuracy to the given experimental data. These suggested models enable to forecast the stiffness degradation of fiber reinforced composite materials with a variety of designs, hence enabling them to anticipate the performance of fiber-reinforced composite materials that are not subjected to experimental limitations.

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