Simulation of Composite Material Fatigue Damage

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Abstract

This paper develops a mathematical model for fatigue damage evolution in composite materials. The characteristics of damage growth in composite materials are studied and compared with those of damage growth in homogeneous materials. Continuum damage mechanics concepts are used to evaluate the degradation of composite materials under cyclic loading. A new damage accumulation model is proposed to capture the unique characteristics of composite materials. The proposed model is found to be more accurate than existing models, both in modelling the rapid damage growth early in life and near the end of fatigue life. The parameters for the proposed model are obtained with experimental data. A numerical example is implemented to illustrate that the proposed model is able to accurately fit several different sets of experimental data.

***Keywords**:* Fatigue; Damage; Composite; Life prediction

1. Introduction

Due to their advantageous particular stiffness and strength, composite materials are employed in a broad variety of aerospace, automotive, and construction applications, with the potential for significant energy savings. In the 1960s, composite materials were initially employed in the rotor blades of airplane engines [1]. Since then, a lot of work has gone into enhancing composite materials' performance. High-temperature applications are another area where composite materials are being studied for use in cutting-edge aerospace vehicles and gas turbine engine parts. There is evidence that using composite materials can lower the total cost of ownership [2].

Components in several of these applications experience cyclic loading. Deterioration in form and function is a cumulative effect of cyclic stress. During the component's and structure's service life, it is preferable that the composites and constituents have good fatigue-resistant properties. Accurately assessing the damage and deteriorated attributes is crucial for ensuring the structures function with high dependability throughout their lifespans.

Preventative maintenance and re- positioning of components can avoid catastrophic collapse if the structure's performance is assessed in advance. Given the past loading history, this type of study should be able to estimate how long the structure has left.

The purpose of this study is to provide a generalized mathematical model that can account for the fatigue behavior of composites. The implications of the different mechanisms of fatigue failure between composite and homogenous materials for fatigue life prediction are investigated. Then, the current techniques for assessing damage in composites are reviewed, contrasted, and debated. To account for the specifics of how composites break down, a new damage evaluation function is presented. To illustrate the use of the suggested function for composite materials subjected to cyclic loads and to illustrate the adaptability of the proposed model for various sets of experimental data, numerical examples are provided.

2. Fatigue of composite materials

Under cyclic loads, fatigue is the primary cause of structural failure. Significant effort has been devoted to studying monolithic materials like metals, with results including the development of fatigue-resistant materials and new approaches to engineering them. prediction. The disparate material qualities of the composite's elements make fatigue analysis and, by extension, life prediction, a challenge. The presence of additional components and the interface areas between the fibers and matrix can have a major impact on the fatigue behavior of a single component. The mix of the composite's constituents as well as the differences in characteristics between the composite's fibers and matrix can greatly affect the composite's fatigue properties.

Since 1967, a large number of experimental experiments have been published on in order to acquire the fatigue characteristics of various composite materials. Empirical S-N curves relating stress and fatigue life have been generated from these experimental data. It has been proposed that these connections be used in design [3]. Based on the data, both linear and nonlinear S-N curves have been proposed [4-9]. Predictions of composite materials' fatigue lives are also made using a nonlinear curve between strain and fatigue life [10, 12]. It is common practice to model experimental data using a linear connection between the maximum stress S and the logarithm of N, the number of load cycles until fatigue failure.

$$S = m \log N + b \qquad (1)$$

directions. Matrix cracks can start in a direction that is perpendicular to the stress. Debonding between the fibers and matrix can also cause cracks to start at the fiber direction contact. Numerous fatigue experiments have been conducted to learn more about fracture propagation in composites when there is a single dominating crack. The fracture spreads along the same plane and in the same direction as the original fracture. This propagation of fatigue cracks has been characterized using the Paris law. However, this is only applicable to composite materials with fibers that are oriented in a single direction. A comparable form of fracture propagation cannot be attained for more general laminates, not even with little loads. Therefore, fatigue analysis of composite materials cannot rely on classical fracture mechanics.

Predicting the fatigue life of buildings made from composite materials may be improved with the use of the idea of damage accumulation. However, direct measurement of fatigue damage is currently impossible. Therefore, Young's modulus or the stiffness of composite materials is commonly utilized to quantify the fatigue damage caused by cyclic loading on a quantitative level. For instance, the following [13] defines fatigue damage in terms of Young's modulus:

where m and b are parameters related to material properties.

After a certain number of cycles, fatigue damage may be evaluated with a fatigue damage accumulation model, which will be explained in the next section, using the projected fatigue life under constant cyclic loading. When the cumulative damage surpasses the critical amount of damage, it is presumed that the composite will fail.

Composite material failure, third

Damage accumulates in composite materials under cyclic stress, leading to cracking or functional collapse of structures. monolithic or homogenous

where D1 represents the total fatigue damage, E0 represents the initial undamaged Young's modulus, and E represents the modulus of the damaged material. Thus, the Young's modulus of the material may be used as a quantitative measure of damage.

The observed Young's modulus or stiffness shortly before the specimen fails completely is not zero, as shown by the experiments. When a material fails, the total accumulated damage is not 1, but 1 minus the Young's modulus at failure (Ef) divided by the initial modulus (E0). Because of this, the final Young's modulus Ef may be used to define a new damage parameter, Ef = E0 - E.

damage accumulates slowly at first in materials with isotropic material characteristics, and A single fracture develops and spreads in a plane orthogonal to the cyclic loading axis. Multiple damage modes, including matrix crazing and cracking, fiber/matrix decohesion and fiber fracture, ply cracking and delamination, void growth and multidirectional cracking, characterize the fracture behavior of composite materials, especially those structures made up of multiple plies and laminates. These modes manifest themselves in composites at an early stage in their fatigue life.

Composite materials have complicated fracture initiation and development processes. Cracks can originate in many places and directions, even in unidirectional reinforced composites subjected to simple loading cases such stress along the direction of fibers.

If Eq. (3) holds, the sum of the damages will be between zero and one.
Many different types of damage may occur on composites because of their complexity. These modalities manifest themselves at the onset of weariness. In the early cycles, the harm adds up quickly. Microcracks start appearing all over the matrix at this point. The fiber-matrix interface is a particularly vulnerable area, leading to debonding. Some weaker fibers may also snap at this time. In the subsequent phase, the rate of damage expansion is low but constant. In the final phase before a fracture occurs, the damage again expands rapidly. Damage accumulation is compared in a schematic format in Fig. 1.

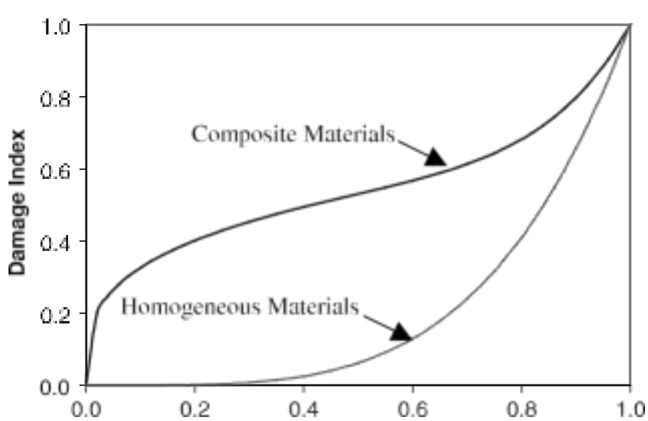

Fig. 1. Sketched fatigue damage accumulation.

fatigue life of the material. But the model is not accurate during the early loading cycles.

Proposed fatigue damage accumulation model

In this research, we provide a novel damage accumulation model that can be used to a wide range of composite degradation scenarios. This theory satisfactorily*N*describes the *N*exponential development of harm in the first and last stages of life. The suggested operation has the form$D = q \frac{n}{} ^{m1} + (1 — q) \frac{n}{}$
$m2$ (6)

Cycle Ratio

mulation as a function of fatigue cycle ratio in composite and homogenous materials. Damage buildup is also shown in measurements of Young's modulus obtained from fatigue testing [9,14,15]. Damage index (specified in Eq. (3)) versus cycle ratio (shown in Fig. 1) are displayed. Number of cycles divided by fatigue life gives the cycle ratio at a particular time. where n is the number of applied loading cycles, D is the normalized cumulative damage, q, m1, and m2 are material-dependent factors, and N is the fatigue life at the corresponding applied load level. The first term, with m1 1.0, captures the features of fast damage buildup in the first few cycles. The second term demonstrates the rapid increase in damage near the fatigue life's conclusion when m2 > 1.0.

In Eq. (6), we give definitions to the parameters in terms of

interest weariness life as

A linear damage summation model was first used to evaluate the fatigue behavior of composite materials by
Nicholas and Russ [16]. Halverson et al. [9] used a
power function in terms of the cycle ratio to evaluate the remaining strength of the material and to calculate the
fatigue life.

where j is a material constant, n is the number of cycles of applied load, Fa is the normalized applied load, and Fr is the normalized remaining strength (both normalized by the undamaged static strength). A steady load has a fatigue life of N hours. To follow the logic of the damage formulation in Eq. (2), the damage accumulation function will likewise be a power function of cycle ratio in mathematics.

$$D = (1 - F_a) \frac{n}{N}^{j} \qquad (5)$$

Both and c depend on the substance being studied. Experimental data on fatigue will yield these parameters. After obtaining damage indices from fatigue testing, the parameters q, m1, and m2 may be calculated using regression analysis. Then, the values for parameters a, b, and c may be determined by Eqs. (7)–(9).

3. Experimental results and curve fitting

Degradation of the material may be explained once the residual strength has been calculated using Eq. (2) or (3). The accumulation functions of damage have also been nonlinear [7,17]. Rapid damage increase may be captured by these nonlinear accumulation functions either in the early stages of life or in the latter stages of life, but not both. For instance, the quick damage increase near the material fracture is not adequately described by the damage model of Subramanian et al. [11], although this model does explain the fast damage growth during early loading cycles. Quick damage expansion is modeled by Halverson et al. [9] as a result of

prove the usefulness of the damage accumulation model you presented. Both the first and second sets are made of 810 O lam- inates and a woven composite, respectively.

Subramanian et al. [11] collected two sets of data for 810 O laminates, at 75% and 80% of ultimate strength, respectively. These are cross-ply laminates with a symmetrical shape (0,903). The epoxy matrix is a hardened HC 9106-3 and the fibers are Apollo. The fibers were sized with a thermoplastic substance and had 100% of their surfaces treated. The fatigue tests were run at a frequency of 10 Hz and a resistance of R = 0.1 [11]. After the laminated composite's Young's mo- duli were

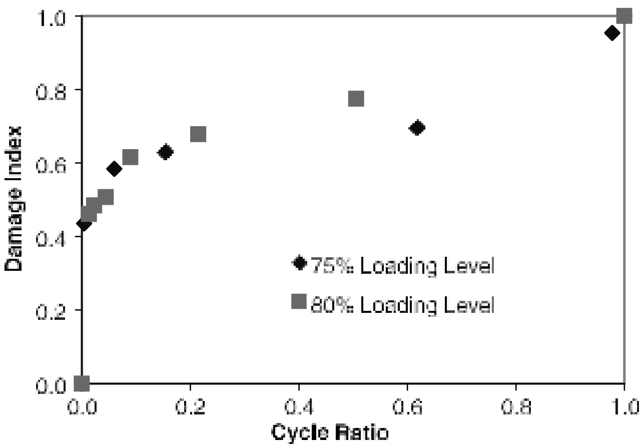

Fig. 2. Measured fatigue damage versus cycle ratio for 810 O lami- nates.

Table 1

Parameters of the proposed function for 810 O laminates

Loading level	*q*	m_1	m_2	*a*	*b*	*c*
75%	0.7380	0.0909	9.1938	0.4147	0.4343	0.4018
80%	0.7789	0.1119	7.5871			

Damage indices were calculated for each condition under tensile fatigue loading based on the number of cycles. Fig. 2 is a scatter plot of the damage indices. The parameters of the suggested model are first determined by analyzing a single data set. The proposed model is then used to fit another set of experimental data using the calculated parameters.

Damage accumulation function Eq. (6) has parameters q, m1, and m2 that may be derived from the damage indices under 75% loading. And then the

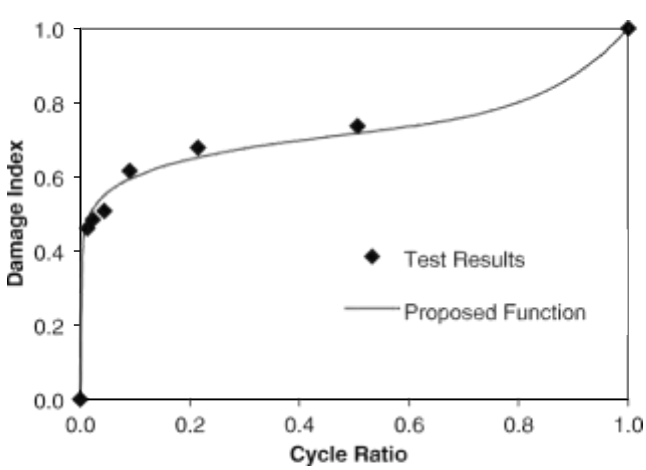

Fig. 4. Experimental observation and model prediction of damage Index for 810 O laminates (80% loading level).

measurements of damage at 80% loading against expected damage using alternative

In Eqs. (7)–(9), the parameters a, b, and c are solved for.

Fig. 3 displays the experimental findings with the proposed model. With an R2 value of 0.9949, it is clear that the suggested function provides a good fit to the experimental data. Table 1 displays the suggested model's parameters. The values of a, b, and c acquired at the 75% loading level are used to calculate the parameters q, m1 and m2 for the damage model at the 80% loading level. FIGURE 4:

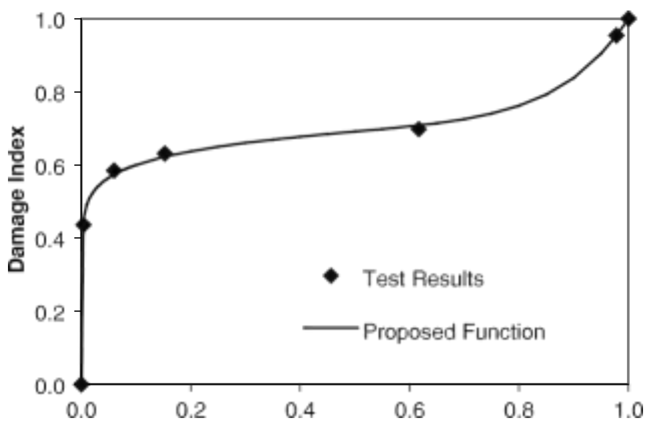

Fig. 3. Experimental observation and model prediction of damage index for 810 O laminates (75% loading level).

model using the data collected at the 75% loading level. In this case, the tested composite material shows good agreement between the expected and experimental findings. This agreement has a very high coefficient of determination (R2) of 0.9644. Table 1 also displays the suggested damage function's parameter values.

To learn more about the fatigue behavior of composites, Kumar and Talreja [15] ran tension-tension fatigue experiments on AS4/PR500 5 harness satin weave samples at 10 Hertz and a R ratio of 0.1. Laminates with a symmetrical orientation (0/902w) underwent tension fatigue testing. Unaged and 6000-hour-aged specimens were compared. The material's Young's modulus was evaluated at varying fatigue cycle counts. Damage indices were calculated from the observed Young's moduli using Eqs. (2) and (3), and the results are shown in Fig. 5.

The experimental data shown in Fig. 5 are now analyzed using the suggested function. Least-squares approach is used to derive the parameters of the proposed function for the damage indices in Fig. 5. Parameters for both old and young males are displayed in Table 2. Figure 6 contrasts the hypothesized function with experimental data. Figure 6 shows that the suggested function well represents the key features of damage evolution in composite materials. Coefficient of determination values

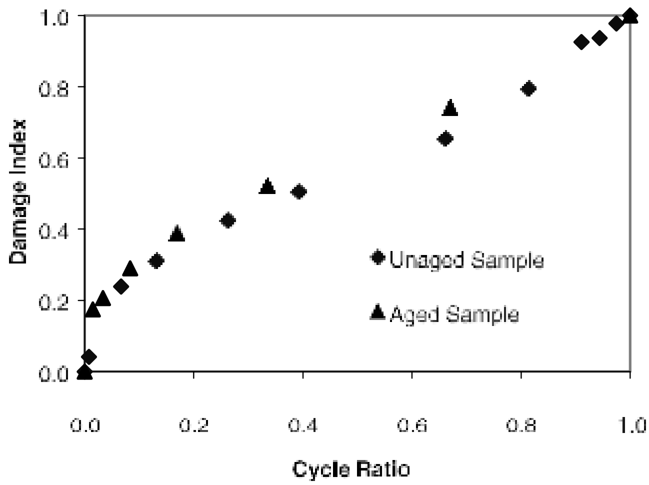

Fig. 5. Calculated damage from measured Young's moduli of AS4/ PR500 woven composite.

Table 2
Parameters of the proposed function for the AS4/PR500 woven com- posite

Material	q	m_1	m_2	
Unaged specimen		0.7755	0.4633	4.1076
Aged specimen	0.7143	0.3535	2.0350	

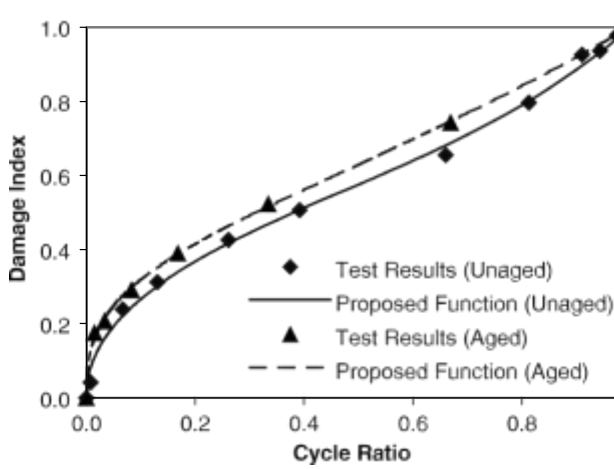

Fig. 6. Experimental observation and model prediction for the AS4/ PR500 woven composite.

R^2 are 0.9696 and 0.9973 for unaged and aged samples, respectively.

4. Conclusion and discussion

This research investigates what causes damage to accumulate in composite materials and how that damage manifests itself. Damage evolution in composites subjected to fatigue loading may be broken down into three distinct phases, as evidenced by experimental results of damage growth. In the initial phase,

When numerous damage modes occur simultaneously within a material, fatigue damage spreads fast. In the second phase, the dam age gradually and steadily rises. In the last phase, fibers continue to break and the damage spreads quickly.

It is proposed that a nonlinear model be used to represent the specific features of damage progression in fatigue-loaded composite materials. The proposed model's parameters are determined by experimental evidence. The measured parameters allow for continuous assessment of fatigue damage. The numerical examples validate the accuracy of the suggested damage function in representing the experimental outcomes. The suggested approach allows for more precise estimation of fatigue damage indices accrued over the course of a product's useful life.

Damage buildup at a variable loading level may be modeled using the same set of parameters, as demonstrated by the 810 O laminate. Very high agreement is seen between the suggested function and the measured damage from experimental tests in the numerical example. For both cross-ply and woven composite laminates, the suggested model is found to be effective.

For fatigue life prediction, an accurate model of the damage progression is crucial. It appears that, for the materials examined, the suggested damage accu- mulation model succeeds with excel- lent precision in this regard. This improves the reliability of fatigue life predictions made with models.

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