FATIGUE DAMAGE IN UNIDIRECTIONAL COMPOSITE LAMINATES UNDER CONSTANT STRESS AND CONSTANT STRAIN LOADING CONDITIONS: A COMPARATIVE STUDY

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ABSTRACT

In this paper the approach to understand fatigue performance of composite laminates is reviewed in the light of a strain-based approach as proposed by the authors. Here, starting from the observation that damage in composite laminates is controlled by the effective strain applied during a fatigue cycle, constant stress fatigue is re-discussed. The strain-based approach allows accounting for the large experimental data scatter usually observed in composite laminates tested under cyclic loading and to give the basis for developing a rationale for reliable fatigue design tools.

KEYWORDS

FATIGUE, COMPOSITE , DAMAGE

INTRODUCTION

The possibility to understand and predict composite material performance under cycling loading has been deeply investigated in the last decades. In the majority of the published studies, fatigue behavior of composite materials has been approached as for metals. Large experimental effort has been spent in determining the S-N for different laminate configurations, stacking sequences, matrix-fiber choice, and so on. Mainly experimental data reported in the literature have been obtained under constant stress amplitude. Additionally, composite strength after cycling has been also used as a critical parameter to characterize material fatigue performance, Laws and Dvorak [1], Hashin [2-3], Allen *et al.* [4].

From all these studies, the following common features arise. Firstly, failure is not a unique concept for composite materials. Traditionally, final failure for metals represents the configuration at the end of life for which the imposed loading conditions are no longer sustained and specimen breaking into two or more parts occurs. On the contrary, complete specimen separation in composite laminates may not occur even under extremely severe damaging conditions. Here, failure intended as loss of performance with respect to the application for which the component is designed for, should be used as a more effective screening criterion in material characterization. A large data scatter always characterize the fatigue life under stress controlled conditions. Usually, small variation of the imposed maximum stress results in a very dispersed data at failure lives. The major consequence is the lack of reliability of the fatigue curve available in published papers for design purposes. Additionally, it has to be noted that still today, the MIL Handbook procedure does not provide any detailed procedure for designing composite material components to fatigue. Finally, the damage development in composite laminates under cyclic loading usually follows clear sequences in the development of the basic damage modes, such as matrix cracking, interlaminar delamination, fiber failure, fiber-matrix pull up, and no new mechanism of failure with respect to quasi-static loading is generated under fatigue.

The presence of a large scatter in the representation of experimental measurement sometimes can be an indicator of low correlation between the dependent and independent variables.

The possibility to better understand the effective composite material performance has been initially offered by Talreja [7] reformulating constant stress amplitude data in terms of imposed strain.

In this paper, fatigue behavior of composite laminates is reviewed comparing material performance under constant stress and constant strain amplitude. This approach confirms the role of the effective applied maximum strain as a governing parameter for fatigue performance estimations. A major outcome is that strain can be actively, reliably and continuously controlled in composite components in service using embedded sensors.

CONSTANT STRESS AMPLITUDE AND CONSTANT STRAIN AMPLITUDE FATIGUE FEATURES

Fatigue testing for composite materials has been traditionally performed under constant stress amplitude loading condition following the same approach used for metals. When loaded, damage can occur in a composite laminate in the form of matrix cracking, fiber failure, interlaminar delamination and fiber-matrix debonding. The sequence of appearance of these basic failure modes is controlled by the lowest strain to failure of the composite constituents. An interesting feature is that no new damage mechanism is introduced by fatigue with respect to the monotonic quasi-static loading. Each of these basic damage modes modifies the material constitutive response. However, transverse matrix cracking, that is the first damage mode to appear both under quasi static and fatigue loading, is the responsible of the major reduction of the material stiffness. Transverse matrix cracking density increases with the increasing of the imposed strain (stress) until saturation occurs, a situation usually described as characteristic damage state (CDS).

According to this, damage in composite laminates has been addressed focusing the attention on the evolution of the matrix crack density with cycles. Even though the relation between the stiffness reduction due to a given crack density is well assessed, the damage kinetic evolution law with cycles still needs to be assessed. As previously stated, this job is made even more difficult due to the large experimental data scatter that arise from constant stress amplitude testing.

Bonora and Newaz [6] investigated fatigue performance of a number of composite laminates, varying stacking sequences, constituents, etc. They found that during constant stress fatigue, cyclic strain amplitude increases as a result of damage that lower material stiffness plus an additional strain ratcheting due to the non complete closure of generated cracks, Figure 1 . Additional strain accumulation can be also induced by visco-plastic material behavior.

If the dominating part of the total accumulated strain is the one due to damage, strain amplitude increases until CDS is reached. After this point, stress amplitude and strain amplitude will be both constant during cycling similar to metals under stabilized cycle loading conditions.

Newaz and Bonora [7] have found that this correlation between stress and damage is inadequate to describe the material damage evolution process as the assumption of uniform stress on the net section is an unrealistic one. In reality, the stress field in a cracked laminate is quite far from being uniform. The multiple transverse cracks shield each other resulting in a very scattered stress field as can be observed experimentally using thermal wave image or photoelastic technique. In essence, this results in a large scatter in composite stress-strain response.

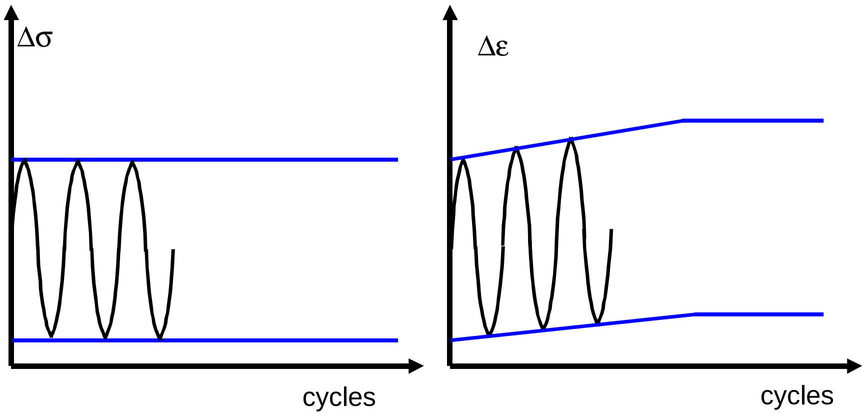

Figure 1 – Strain amplitude evolution under constant stress amplitude fatigue loading in unidirectional composite laminates.

Bonora and Newaz [6] proposed an approach to stiffness reduction in composites in term of the effective applied strain. They found that using strain as independent variable, the damage curve obtained from several specimens is characterized by a very low scatter confirming the fact that damage *D* as a function of strain, ε, is a reliable material property degradation indicator in fatigue. Here, damage evolution with strain , defined as the complementary normalized stiffness loss for the laminate, can be accurately described as:

$$D(e) = D_0 + \left[D_{cr} - D_0\right]\left[\frac{\ln(e/e_{th})}{\ln(e_{CDS}/e_{th})}\right]^{\frac{1}{M}} \qquad (1)$$

where D_0 is the initial damage, D_{cr} is the value of damage at CDS, ε_{th} is the threshold strain for which damage process, i.e. matrix cracking, is activated; ε_{CDS} is the strain at CDS and *M* is a material constant. This equation has been successfully verified for a large number of brittle composite systems both ceramic and polymeric.

In addition, it has been found that, if the effective accumulated strain is correlated with cycles, the damage curve resulting from fatigue is the same as for quasi-static loading, as given in figure 2, suggesting the absence of new damage mechanisms due to fatigue.

If the key parameter to understand damage accumulation in composite laminates is the effective applied strain it follows that damage evolution observed under constant stress amplitude is not a material feature or property.

Let us assume to apply a stress amplitude Ds on a given laminate. If the resulting maximum strain associated with the applied maximum stress overcomes the material strain threshold (0.025 in Figure 2), some damage is produced in the laminate in the form of transverse matrix cracking. Since the damage curve is very steep in the first part (lower strain), small strain changes generates large damage amounts.

At the end of the first cycle, the material stiffness is changed as a result of the damage and a residual strain can also be measured. In the following cycle, in order to reach the previous maximum stress with a lower stiffness, a larger maximum strain value will be reached and consequently new damage will be generated. This accumulation process will continue until CDS stage is reached. It follows that crack density accumulation has to increase faster in the early stage of fatigue life and slow down with the increasing of cycles. This has to result in a concave accumulation curve as effectively observed in the experiment.

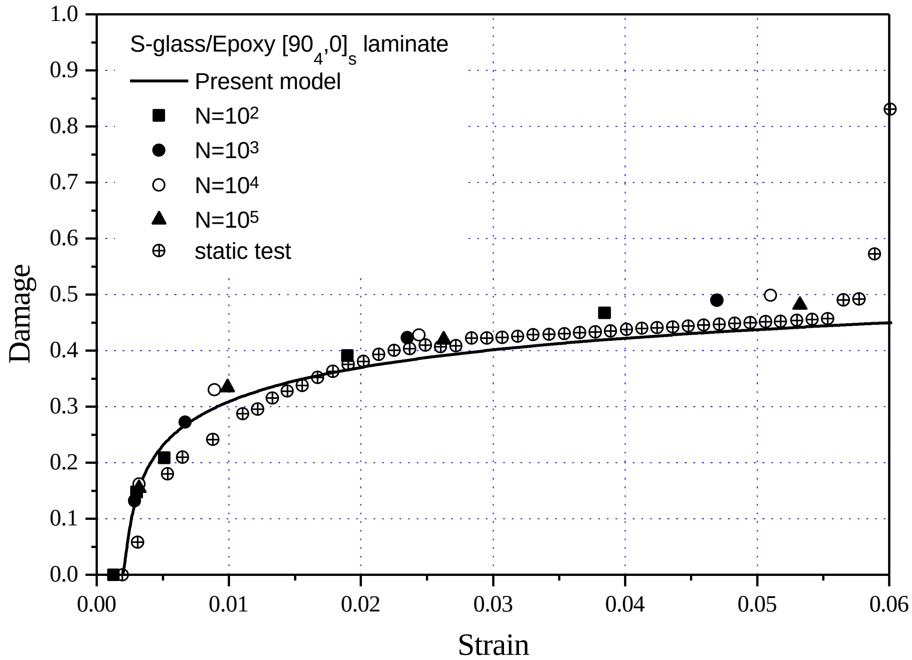

Figure 2 – Comparison between the quasi-static and the fatigue damage evolution with strain in glass/epoxy laminate

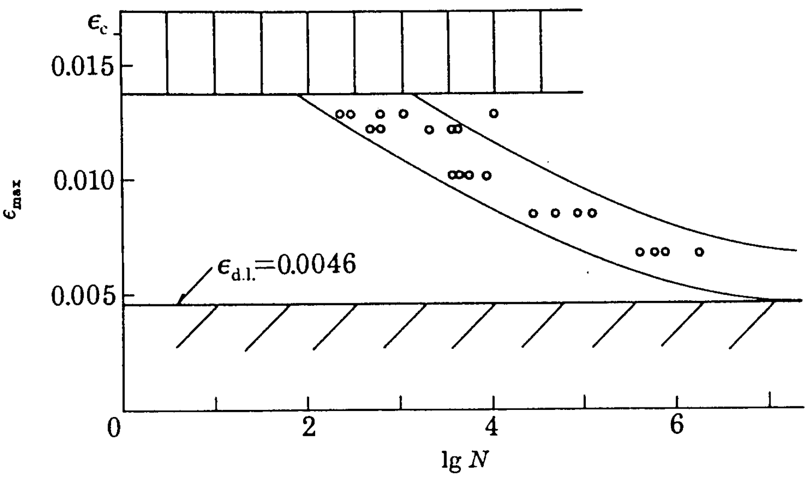

Figure 3 – Fatigue life diagram for glass/epoxy laminate (Talreja, 1987).

If the maximum strain associated with the stress amplitude is below the strain threshold no damage occurs and theoretical infinite life is expected. This value is characteristic for the material and stacking sequence since the laminate lay-up gives constraint condition for the occurrence of transverse matrix cracking. On the other side, if the maximum stress is high enough to develop CDS condition in the laminate during the first cycle, no further stiffness loss will occur in the following cycles due the already occurred saturation in the damage curve. In this case failure will occur as a result of fiber failure.

This scenario finds confirmation in the fatigue life diagram as proposed by Talreja and given for example in figure 3. The only objection comes from the possibility to convert constant stress amplitude data to strain. As discussed, this is only possible for stress above CDS, in the lower range strain accumulation with cycles need to be evaluated and accounted for.

If damage is associated to strain and fatigue does not introduce any new damage mechanism, it follows that constant strain amplitude cycling should not result in material fatiguing. Bonora *et al.* [8] have verified this assumption in glass/epoxy laminates. In addition, experimental tests performed on laminates previously damaged at different D values, shown the absence of evolution of damage state in the usual fatigue life range ($< 5E10^6$ cycles). It has to be said that even though the under constant strain amplitude the damage generated in the first cycle does not growth, additional damage mechanism such as localized delamination can initiated as a result of internal friction. According to the authors experience these phenomena are activated in the very late part of the laminate life with a very weak effect on the material stiffness changes.

CONCLUSIONS

The strain-based approach proposed by the authors to describe fatigue performance of composite laminates seems to indicate a better way to understand material response under stress controlled conditions.

The experimental tests performed on different laminate stacking sequences confirm that under strain controlled condition no damage evolution occurs. Damage is controlled by the maximum strain in the first cycle.

Under constant stress amplitude, strain increases with cycles as a result of the change in stiffness, resulting in an apparent damage evolution, as usually observed in the literature where fatigue resistance is evaluated looking at the number of cycles before failure.

The proposed framework is consistent with the fatigue life diagram proposed by Talreja that represent a valid way for developing a reliable tool for fatigue design.

It is the authors' opinion that the evolution of strain under constant stress fatigue should be more thoroughly investigated in order to come up with a relationship to correlate strain evolution with cycles and damage.

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