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Editorial

Evolution of Fatigue Behavior Characterization of Polymer-Matrix Fiber-Reinforced Composite Laminates

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Editorial

There are currently three approaches to characterize and quantify the fatigue behaviour of composite laminates that are, Fatigue Life Modelling and Prediction, Phenomenological and Empirical Modelling, and Progressive Damage Modelling. These approaches constitute the evolution that is driven by ever expanding industrial needs and academic pursuit, and assisted by perpetual technological advances in experimentation capabilities.

In the first approach of Fatigue Life Modelling and Prediction the individual material degradation mechanisms are not directly concerned with, rather the determination of stress-life relationships based on experimental data is concerned with and the failure criteria or the residual strength determination is established based on these relationships, for the specific composite laminate. The prediction of the stress-life relationships of unidirectional laminates with arbitrary ply orientations is performed based on that of a laminate with fibers aligned in one orientation by suitable characterization methods. Such works are mainly based on a deterministic framework. Statistical methodology has been used but to a very limited extent. These works consider in each case specific constituent materials, ply stacking sequence, loading condition and more importantly a specific laminate thickness. Distinction between different individual failure mechanisms and to some extent their interactions have been incorporated. Use of in-plane stress state assumption, which is acceptable for individual ply and thin laminate, is inherent in most of these works. For the fatigue life prediction, based on a suitable theory of stress interactions, such as the quadratic approximation theory, the failure criteria were expressed in terms of the stress-life relationships for specific failure modes of the laminate such as fiber failure, matrix failure and delamination.

The second approach of Phenomenological and Empirical Modelling endeavors to take into account at least to some extent the degradation of an appropriate mechanical property of the ply material, especially the stiffness or the strength. Residual stiffness models characterize the degradation of the stiffness of composite ply through non-destructive testing and evaluation techniques. Residual strength models have been established based on strength reduction as cyclic loading proceeds. The strength of the material may remain almost constant until a certain number of fatigue cycles and after that the strength may be abruptly reduced to a very small magnitude. Alternately, after reaching a threshold number of fatigue cycles, the strength may decrease gradually and monotonically as a function of cyclic loading frequency and stress ratio. This approach has limitations that (a) a large number of parameters have to be determined based on

extensive experimental data, (b) the models were not evaluated for a wide range of loading levels and frequencies, and (c) the experimental data used correspond to thin laminates.

The third approach, Progressive Damage Modelling is based on advanced analytical modeling methodologies such as cohesive zone modelling and they have been developed considering the progression of a specific type of damage in the laminate. This approach possesses the dual capability of prediction of the number of cycles to failure and prediction of mechanical property degradation such as stiffness and strength degradation. Two major groups of such models, models predicting damage growth and models predicting residual mechanical properties, have been developed. In the former, models characterize accumulation of specific damage types, such as matrix cracks and delamination. In such works, adoption, adaption and extension of damage evolution models that were originally proposed for metallic materials have been the routes followed. The model parameters are to be determined from experiments on specific laminate samples. Such models predict the residual mechanical properties of the laminate based on the relationships between the residual mechanical properties and the specific damage types. Extensive material testing is involved in this approach. Fatigue tests of laminate specimens until various number of cycles followed by a static test until failure is involved in addition to fatigue tests to final failure of laminate specimens. In this approach two distinct phases of fatigue behavior are hypothesized to be present, that are, Damage Initiation Phase and Damage Propagation Phase. Specification and clear demarcation of these two phases are left open to speculation and/or individual judgment and preference, and one has to define themselves what kind of damage aggregation happens in the laminate that eventually leads to final failure, again leaving the specification of final failure to individual judgment and preference. For thin, moderately-thick and thick laminates, the corresponding damage aggregation processes are assumed to be the same.

In modern mechanical, civil infrastructure, and aerospace engineering applications, composite laminates of different types and sizes have been in use, and the manufacturing processes used have been constantly evolving. A wide spectrum of laminate types and geometries and constituent materials are to be designed and developed for use in adverse service environments, and a wide spectrum of manufacturing methods have to be used to produce and assemble them into final engineering product. A blanket application of any one of the above- mentioned three approaches is not appropriate and reliable. There are severe limitations associated with the existing approaches: the plane-stress state assumption is not valid for moderately-thick and thick laminates, same damage aggregation or accumulation process is not applicable for laminates of different thicknesses and shapes, the number and types and characteristics of failure modes are vastly different between laminates of different thicknesses and geometries, effects of hostile service environments including humidity and temperature have not adequately been incorporated and so on. For moderately-thick and thick laminates, the use of plane stress state assumption is not valid since considerable through-the-thickness normal and shear stresses get developed in these laminates. In addition, in thick composite laminates, a dominant failure mode is the delamination due to the interlaminar shear stresses and the out-of-plane normal stress. In addition, especially in thick laminates, most frequently, thermally-induced residual stresses are present and significant. These two key aspects of thick laminates have not been considered in the majority of failure criteria developed to date based on the above mentioned three approaches.

Hence there is a current and urgent need to drive the evolution of study of fatigue behavior so as to incorporate the critical features of moderately-thick and thick laminates and complex effects of service environments. A hybrid or mixed approach needs to be developed based on the existing three approaches, which I would call as "basic approaches", and moving beyond the deterministic framework is essential to develop a generic and universal approach that would ensure required levels of safety and reliability in industrial and engineering applications.

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