Micromechanics Based Continuum Damage Model for Ply Failure in Unidirectional Composites

Synopsis

Composites are increasingly used in advanced light-weight structures, especially modern aircraft structures. This makes it imperative to understand damage mechanisms and their effects, in composite structures. Most aircraft structures are subjected to cyclic loads, which can lead to progressive growth of damage till failure of the component. Hence, life of the component becomes important both from design and certification point of view. The main objective of this study is to understand the effect of the damage mechanisms on the effective material response parameters and to develop a simple continuum mechanics based damage model for unidirectional composites.

Several growth models have been proposed in the literature, starting from the first ply failure theory, progressive ply failure theory, and others (for example the world wide failure exercise[1]). A major problem with these models is that they could predict either the initiation of damage or provide a crude global model for ply-wise damage. These models could not predict the point-wise distribution of damage or its evolution. For the past thirty years, significant focus has been given to the development of continuum damage models (CDM) which link the micro, meso and macro levels. This is done by introducing internal variables (damage variables) to account for damage mechanisms and their evolution. The evolution laws for damage variables are derived based on the principles of thermodynamics of irreversible processes. These models are of various types which represent damage either through a tensor of second or higher orders, or through reduced damage parameters. However, these parameters, most often, do not have a direct connection to the measurable damage sizes at the micro/meso level. Most of these CDM models are based on micromechanical studies conducted with simplifying assumptions about either the damage mechanisms or the mechanics at the microlevel.

A major problem with the existing damage mechanics based models is that the stiffness properties become zero as the damage reaches its critical value ($d_i = 1$). This leads to

[1]Hinton, M. J., Kaddour, A. S., Soden, P. D. (ed.) *Failure criteria in fibre reinforced polymer composites: The world-wide failure exercise*, Elsevier Sci Ltd, 2004

a material singularity at a point, where the stiffness values become zero. Thus a cut-off damage value is often employed in the evolution model to prevent the stiffness values from becoming zero.

In light of the above discussion, the thesis focuses on developing a detailed micromechanical analysis at the level of the constituents (fiber and matrix) in order to understand the local state of stresses and strains. Damage mechanisms are identified based on these stresses (and strains) and the damage parameters are characterized in terms of damage sizes of these damage mechanisms at the microlevel. Based on the literature and available experimental evidence, the microlevel damage mechanisms identified are: *1*) Fiber breakage, *2*) fiber-matrix debond, and *3*) matrix cracks. The micromechanical analysis is done, using the mathematical theory of homogenisation, on a representative volume element[2] (RVE) with and without damage.

From the micromechanical analysis, understanding of influence of each of these damage mechanisms on the degradation of the primary stiffness coefficients (such as axial stiffness, transverse stiffness, Poisson's ratio and shear stiffness) is obtained. Based on this understanding, the study tries to develop a simplified model for stiffness degradation in terms of different damage mechanisms and their sizes. It is shown in the study that based on the characterization done, the stiffness values will never degrade to zero.

The study also systematically brings in the effects of volume fraction, which is normally ignored in the study of damage in the literature. Further, the study focuses on implementing a simple model for residual stresses developed due to cure process. The model is based on cooling down of completely cured composites from cure temperature to room temperature. The model assumes that the curing is complete before cooling down process and there is no change in the elastic properties during the cooling down process. Based on the study of residual stresses, a detailed model is developed for the degradation of the coefficient of thermal expansion in terms of damage. This brings out a very important feature which is often missed in the damage modeling - that of the additional residual strains being generated due to damage (which can be linked to the thermal cure induced strains).

All these studies are used in developing an expression for macrolevel free energy, in con-

[2]Representative Volume Element (RVE) can be defined as the volume element that is small enough to be representative of local material response yet large enough to represent the average material response.

sonance with a widely accepted damage model called *damage meso model for laminates* developed by Ladeveze[3] *et al.* . Based on this expression, constitutive equations for macrolevel stresses and thermodynamic forces, corresponding to damages, are derived. Using arguments from continuum thermodynamics and necessary consistency condition on the dissipation of energy, a simplified model for evolution of damage is developed in this study.

The evolution model is defined in terms of the macro-stresses, but is based on the micromechanical observations and thought experiments. The parameters in the evolution model are obtained from the available data from experiments conducted on the selected composite laminates. The damage initiation criteria is also defined in terms of macro-stresses, but is based on stress concentration factors in the critical regions, identified from the micromechanical analysis.

It is shown in the study that the simplified models developed are effective in capturing the observed rupture of a damaging coupon of any unidirectional composite, in the absence of laminate level delamination. Specifically, the model is applied to predict the response of several laminates such as $[\pm 45]_s$, $[\pm 67.5]_s$, $[0/90]_s$, $[-12/78]_{2s}$, and $[67.5/22.5]_{2s}$. It is shown in the study that the model predictions are very close to the experimental results. From the evolution curves of different damage modes in each ply, some interesting observations can be made about the underlying physics, e.g., the interplay between various damage mechanisms and the coupled growth of various damages depending on the loading in the ply.

It is shown that in the transverse direction the inelastic strain is caused due to both matrix plasticity and change in the residual strain due to damage. This effect has been termed as *shift in the initial state* due to progressive damage.

This study further attempts to estimate the length scale of influence of different damage modes, through their effect on the stiffness properties in the neighboring RVEs. This nonlocal effect manifests differently in different properties. The maximum length scale of influence along the fiber direction and in the transverse direction is estimated. This compares well with the accepted influence length scales available in the literature.

The CDM model proposed in this study, has the potential to allow for easy characterization of response of composites in terms of constituent behavior. The model provides a bridge

[3] Ladeveze, P. and Dantec, E. L. "Damage modelling of the elementary ply for laminated composites", *Composites Science and Technology*, 1992, 43, 257-267

between the micromechanics and the CDM based meso/macro models.

Some of the possible extensions to this study are: *a*) Generalised damage model for laminates by considering the damages that occur at the laminate level, such as delamination, *b*) study incorporating the effect of interaction of several damage modes (interaction and coalescence model), *c*) detailed analysis of the growth of softening regions in the matrix (microlevel incremental plastic analysis), *d*) study of the effect of other classes of matrix materials (for example thermoplastics) on damage initiation and evolution, *e*) extension to the dynamic loading cases, *f*) extension to include the stochastic nature of the constituents, and *g*) modeling of compressive failure.