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A synergistic damage mechanics based multiscale model for composite laminates subjected to multiaxial strains

John Montesano, Chandra Veer Singh *

Materials Science and Engineering, University of Toronto, 184 College St., Suite 140, Toronto M5S 3E4, Canada

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A multiscale model based on synergistic damage mechanics is developed for predicting the elastic response of symmetric composite laminates containing matrix cracks in plies of multiple orientations, and subjected to an arbitrary multiaxial strain state. On the micromechanical scale, the proposed multiscale modeling approach invokes three-dimensional finite element analysis to characterize the multiaxial damage state within the cracked multidirectional laminate, and evaluate damage constants required in the damage constitutive model. These damage constants capture the ply constraint effects acting on the surface displacements of the developed matrix cracks in all off-axis and on-axis plies. The representative volume element describing the applied multiaxial stress state within the laminate is developed through finite element models using periodic boundary conditions, which are necessary to accurately represent the physical problem. The developed micromechanical models also allow for prediction of the laminate's shear deformation response. The model is shown to accurately capture the nonlinear stiffness degradation exhibited by cross-ply, quasi-isotropic and angle-ply laminates containing matrix cracks in multiple plies and subjected to various multiaxial stress states. The prediction results are validated by available experimental data and compared with independent three-dimensional finite element calculations. The multiscale model can easily be implemented into a commercial finite element software package in order to predict stiffness degradation in composite structures. This will provide a means to predict the integrity and durability of these structures, and ultimately lead to damage-tolerant designs.

1. Introduction

For a wide range of practical structural applications, orienting the plies of composite laminates along multiple directions is required to meet specific directional strength and stiffness requirements. A key issue with the design of multidirectional laminates is that their microstructure is quite complex, leading to a complex stress state upon loading. In these laminates, local matrix cracks tend to develop in multiple directions simultaneously as the structure is progressively loaded (Tong et al., 1997). These subcritical matrix or ply cracks, which are contained within the individual plies and are usually oriented along the respective fiber directions, do not cause immediate failure but rather accumulate during loading. This consequently leads to a complex three-dimensional problem as cracks in multiple orientations evolve simultaneously with differing rates and densities (Singh and Talreja, 2009). The difficulty of the problem increases further when the laminates are subjected to complex multiaxial stress or strain states representing the real application of composite structures. In

* Corresponding author. Tel.: +1 (416) 946 5211; fax: +1 (416) 978 4155.

E-mail addresses: john.montesano@utoronto.ca (J. Montesano), chandraveer.singh@utoronto.ca (C.V. Singh).

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such situations, the multidirectional crack state will be subjected to additional crack driving stress components, which will ultimately alter the resulting material behavior. Since practical structures are subjected to multiaxial loading, or more generally local multiaxial stress states, it is important for corresponding prediction models to account for the influence of these stress states on matrix cracking. This is essential for accurately predicting the integrity and durability of practical structures, and for performing progressive failure analysis. This is in fact a main focus of the third world-wide failure exercise (WWFE-III) conducted by Kaddour et al. (2013), in which the evolution of subcritical damage and its effect on the mechanical response of composite laminates is considered. If a multiaxial progressive damage model can be integrated with a non-destructive evaluation (NDE) technique, a real-time structural health monitoring tool can be developed. This will effectively lead to the design of safer and more cost-effective composite structures.

With respect to its undamaged state, the behavior of a laminate in the presence of subcritical matrix cracks is altered, and therefore the local damage state must be considered in prediction models in order to accurately capture this inelastic material behavior and to determine the ultimate material strength or stiffness (Varna et al., 2001). A reduction in the laminate stiffness properties is one of the main outcomes of the evolving damage state. Currently, there are no rigorous and comprehensive prediction tools to asses the response of such multidirectional laminates undergoing progressive damage development in the form of ply cracks in multiple-oriented plies under multiaxial loading. Current designs are far too conservative since they do not account for the evolving damage state during the design process, and as a result the laminate capabilities are not fully utilized. A number of models have been developed in recent years that attempt to predict stiffness degradation in composite laminates resulting from ply cracking. Many analytical models were developed with this purpose, including the shear-lag model by Highsmith and Reifsnider (1982), the variational models by Hashin (1985) and Nairn (1989), and the self-consistent approximation by Dvorak et al. (1985). Most of these models only consider cross-ply laminates and are not suitable for practical scenarios involving multidirectional laminates consisting of a mix of both on-axis and off-axis plies.

Additional models that correlate matrix cracking with stiffness degradation are those based on the principles of continuum damage mechanics (e.g., Allen et al., 1987; Ladeveze and LeDantec, 1992; Talreja, 1985). The main advantage with such models is that the effects of particular damage modes can be directly incorporated into the constitutive equations through the use of damage tensors. However, a key drawback of continuum-based damage models is their reliance on extensive experimental testing for calibrating the material damage parameters. In order to alleviate this problem, Talreja (1996) proposed a synergistic damage mechanics (SDM) approach that combines the strengths of micromechanics and continuum mechanics to produce a versatile multi-scale methodology. The methodology relies on computational micromechanics, in lieu of experimental testing, to calibrate the material damage parameters. Following this approach, a predictive model for off-axis ply cracking in multidirectional laminates was later developed by Singh and Talreja (2009, 2010) to predict the behavior of laminates containing multidirectional ply cracks. The model has also been applied to conduct several test cases of the WWFE-III exercise (Singh and Talreja, 2013). To understand the underlying concepts and the details of the SDM methodology, the reader is referred to Talreja and Singh (2012).

It should be noted that only a few models reported in the literature account for multiaxial loading, or more generally the local multiaxial stress states inherent in multidirectional laminates. Recent studies have been reported in which local multiaxial stresses and their influence on ply crack initiation and development are accounted for (e.g., McCartney, 1998; Mayugo et al., 2010; Vyas and Pinho, 2012; Laurin et al., 2013; Chamis et al., 2013; Kashtalyan and Soutis, 2013; Flatscher et al., 2013). Nonetheless, most of the reported models either limit their application to unidirectional or cross-ply laminates, or to multidirectional laminates containing only cracks in one transverse direction. Furthermore, they simplify the inherent complex boundary value problem by assuming that a two dimensional geometric representation of ply cracks is sufficient. Such a two dimensional representation of the problem does not accurately capture the local crack behavior and the surrounding stress state, and thus a three dimensional solution becomes necessary when multiple ply cracks are present (Singh and Talreja, 2009). In addition to the above, many of the indicated models rely on extensive experimental data for their calibration, which is seen as another limitation. Finally, a number of these models do not consider the evolution of discrete damage modes and the influence of the constraining effect between the adjacent plies in a laminate.

The focus of this study is to improve the capabilities of the aforementioned multiscale SDM approach by including multiaxial capabilities in the prediction methodology. Specifically, emphasis is placed on expanding the capability of the micromechanics computations in order to account for multiaxial effects on stiffness degradation, and to include the capability of predicting shear modulus degradation. The long-term goal is to predict damage evolution in practical composite components subjected to multiaxial stresses (see Montesano and Singh, 2015), and the current study is the first step towards this goal. A brief overview of the SDM methodology is presented in the subsequent sections, with emphasis on the laminate constitutive laws and the micromechanical computational models. The prediction results for three types of multidirectional laminates (cross-ply, quasi-isotropic and angle-ply) is then presented along with a rigorous discussion. Finally, the main findings of the study are outlined in the conclusions.

2. Synergistic damage mechanics model

2.1. Damage characterization in multidirectional laminates subjected to multiaxial strains

Consider a multidirectional laminate consisting of unidirectional on-axis, off-axis and transverse plies as shown