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Probabilistic strength based matrix crack evolution model in multi-directional composite laminates under fatigue loading

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ABSTRACT

A model to predict the matrix crack evolution in multi-directional (MD) polymer matrix composite laminates under in-plane fatigue loading is presented in the current work. Unlike matrix crack evolution under static loading, the matrix cracks in off-axis plies do not form tunneling cracks under fatigue loading; rather, they initiate and grow with increasing load cycles. A probabilistic strength based criterion for matrix crack initiation in off-axis plies based on a Weibull distribution for in situ ply strength variation has been used. An oblique co-ordinate based shear lag analysis has been used to estimate the stresses in the cracked laminate. Smith Watson Topper (SWT) parameter has been used to model the number of cycles to initiate the first matrix crack, and log-normal probability distribution has been used to handle the scatter in crack initiation life. The matrix crack growth rate has been modeled using Paris law based on mixed mode effective stress intensity factor. Using the crack initiation curve and strength degradation based on Palmgren-Miner damage rule, new crack initiation has been simulated. Few parameters needed for the threshold stress intensity and saturation crack spacing have been identified from a reference stress data of cross-ply laminate. The crack density evolution has been simulated for cross-ply and MD-laminates under various constant amplitude in-plane fatigue stress levels. The matrix crack density evolution and its stiffness degradation predictions with the number of cycles have been compared with existing experimental values. A good correlation is found to exist between the experimental data and predictions for both cross-ply and MD-laminates.

1. Introduction

Polymeric composite materials are extensively used as structural materials in various applications like aircraft structures, wind turbines, etc., due to their high specific strength, stiffness, near net shape manufacturing, high corrosion, and fatigue resistance. Composite structures undergo multi-scale progressive damage during their service life, which is subjected to fatigue loading. The structural integrity of such a structure is compromised due to these progressive damage events [1,2]. Early development of fatigue life prediction of fiber reinforced polymer (FRP) composites during 1970's was mostly influenced by metal fatigue experience [3,4]. The detailed systematic study of mechanisms and behavior of FRP's under fatigue loading were studied by [5,6] in early 1980's. One of the first damage modes under fatigue loading of multi-directional (MD) FRP laminates is matrix cracking in the off-axis plies. These matrix cracks initiate first in the plies making the maximum off-axis angle with the loading direction. Matrix crack density (number cracks per unit length) increases with increasing number of fatigue cycles and reaches a saturation value called "characteristic damage state (CDS)." Following CDS, delamination was observed to start at the matrix crack tips growing slowly and steadily. Fiber breaking was seen at all the above stages. In the final stages of life, linking up delamination, the complex interaction of matrix cracks and fiber breaking was observed leading to failure of the laminate. Reduction in stiffness of the composite is observed continually during fatigue and is an indication of the progressive damage mechanisms detailed above. Initially, a steep reduction in stiffness is observed due to matrix cracking followed by the linear reduction in stiffness due to delamination mechanisms; finally, a sudden rapid reduction of stiffness occurs in the final failure stage.

Fatigue in continuous MD-FRP's are influenced by many factors, namely, fiber type, matrix type, type of reinforcement structure, laminate stacking sequence, environmental conditions, loading conditions (frequency, stress ratio), boundary conditions [1], thickness, ply location and constraint, initial damage, material and geometric non-linearities, single mode and multiple modes of damage and manufacturing processes [7]. Due to the complexities of progressive fatigue

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damage mechanisms that arise due to combinations of parameters as mentioned earlier, fatigue life prediction in FRP's is under active research. There have been studies to understand the various damage modes and their effect on structures. As mentioned earlier, matrix cracking is the first damage mode observed during fatigue and static loading. Extensive experimental observations on the nature of matrix cracking under fatigue loading have been studied and reported in the literature as summarized below:

1. As discussed earlier, matrix crack initiates in the off-axis plies and propagates steadily reaching CDS under a constant amplitude fatigue loading. For a higher maximum cyclic stress (σ_{max}), matrix crack initiation occurs at lower number of cycles; for lower σ_{max}, matrix crack initiation occurs at higher number of cycles. CDS values were observed to increase with the increase in σ_{max} [8–10].
2. Matrix cracks under fatigue loading appear to initiate at the free edges; however, these cracks span the thickness instantaneously that then grow progressively along the width with increasing number of cycles [11]. If the σ_{max} is above a certain threshold (static load for initiation of matrix crack), tunneling cracks spanning the width have been observed. Below such values, matrix cracks initiate after a certain number of cycles depending on the stress levels [12].
3. The matrix crack initiation plane is normal to loading direction in case of cross-ply laminates; however, in MD laminates, shear cusps in the fracture surface indicative of shear stress contribution, have been observed.
4. The number of cycles to first matrix crack initiation is related to the applied σ_{max} based on the classical Basquin's type power law relation.
5. Crack initiation life shows a large scatter of more than two orders of magnitude [10,13].
6. No change in crack initiation life for the flat and tubular specimens has been observed [14].
7. The matrix crack growth rate (MCGR) has been observed to be constant under the constant amplitude fatigue loading for a particular ply in a laminate. MCGR does not depend on the matrix crack length [10,15,16].
8. MGCR has been found to be dependent on the thickness of a ply in the laminate; thicker plies in the laminate exhibit faster MGCR as compares to thinner plies of same orientation for the same applied far-field fatigue loading [10,14]. In particular [14] observed that the MGCR in $-50°$ ply of $[0/50_2/0/-50_2]_s$ GFRP laminate was ten times faster that of the MGCR in $+\ 50°$ ply under the range of fatigue stress levels studied. The thicker ply thickness is 1.88 times of the thinner ply.

Early modeling efforts to include matrix cracking in fatigue life predictions have been carried out for the cross-ply laminates to obtain the life until CDS using stress-life (S-N) curves for the 90° layer; remaining life of the cross-ply was assumed to depend on the 0° layer fatigue behavior [17]. Similar studies have been carried out on composites containing off-axis plies [18]. Band models for cross-ply laminates have been proposed wherein the plies are divided into bands and crack initiation life in each band has been simulated using local stress fields and Palmgren-Miner (PM) damage law. Propagation from one band to another band has been modeled using a crack propagation law based on local maximum cyclic stress, normally distributed strength, and stress level at first crack initiation [19]. Transverse matrix cracking under fatigue loading at different temperature levels have been estimated using PM model and S-N curves of 90° lamina. The cracks are assumed to form as tunneling cracks by the authors [20]. In both the above studies, good agreement with experimental observations has been reported for cross-ply laminates.

There have been limited studies on the matrix crack evolution of MD-laminates under fatigue loading. In recent times, studies have been carried out to simulate matrix crack evolution under fatigue loading using physical phenomena observed from experiments. There are only two available studies for the prediction of matrix crack density evolution of MD laminates by [21,22]. Carraro et al. used local hydrostatic stress (LHS) and local maximum principal stress (LMPS) based crack initiation, and energy based propagation laws to estimate the crack density evolution. The stress analysis was carried out by shear-lag approach developed by the authors. Weibull based statistical strength and life variations was assumed. Initial crack length of 2.7 mm was assumed based on the experimental observations of crack length measurement. The lamina was divided into 0.1 mm elements. An approximate expression for energy release rate (ERR) was used to quantify the crack tip. It was postulated that below mode mixity of 0.5, the propagation is controlled by mode I; for other cases, equivalent ERR based on mixed mode scenario has to be used. The threshold value for the material was assumed to be 10% of the critical ERR of the material. It was also recommended to use lower threshold values in order to obtain conservative predictions. Excellent agreement with the experimental observations was reported. A more refined model using similar concepts and global-local damage models by [22,23] was been developed. To simplify the model formulation, matrix cracks were assumed to form at edges. Model parameters required for simulations were obtained from cross-ply laminate fatigue and few MD static data. The critical ERR for unstable crack growth was assumed. Multiple experiments with constant amplitude (CA) and block type loading were carried out. Weibull statistics were used to handle the scatter in initiation and propagation data. When the above models were applied across different laminates, excellent agreement in prediction was reported. However, in few laminates under study, there have been deviations from the prediction and experiments. The authors reasoned that the initiation of cracks had been observed all over the volume, not only from the one edge, which may have different growth rates. There are several zones of delamination also observed at higher load levels studied and such effects were not included in the model. The above models use finite element analysis (FEA) for the estimation of parameters required for simulations. In the complex cracking scenario of MD laminate, the generation of FE model for various crack geometries and boundary conditions can be quite cumbersome.

There have been numerous models to account for residual property under a given damage state. The classical one is based on ply discount method. In this approach, the stiffness of cracked ply is assumed zero, and the properties are re-evaluated. An account of this method is given in [24]. However, the main shortcoming of this method is that cracked ply can also contribute to load sharing by shear transfer through nearby plies. There have been numerous methods based on 1D stress analysis or shear lag analysis by [25], 2D stress analysis using variational method by [26], 3D stress analysis using plane strain assumption by [27], damage mechanics concept has been used by [28,29], and fracture mechanics (dilute formulation) by [30]. The models based on stress analysis are only able to predict the residual stiffness properties of cross-ply laminates. The more general MD-laminate cracking needs complex boundary conditions, and no closed-form analytical solutions are possible. Recently, FEA was used to estimate the residual properties of such complex ply orientations [31]. An analytical model based on oblique coordinates has been proposed by Yokozeki for estimating thermo-elastic properties of MD laminate under in-plane loading [32–34]. These models discussed above do not treat the evolution of cracking and residual properties in a common framework. Other models based on different physical phenomena are also proposed in the literature. [35] show that using thermography, a more quantifiable damage matrix based on thermodynamic entropy can be proposed. The kinetic theory based models were recently proposed in [36].

There have been models to study matrix crack initiation, evolution, and its effect on stiffness under static loading [37–39]. The approaches to model matrix crack initiation and evolution in composite laminates has been approached based on strength or energy [37]. Strength based models usually do not agree well with experiments; however, if