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TENSION FATIGUE ANALYSIS OF WOVEN COMPOSITE LAMINATES

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ABSTRACT

The three major fatigue damage mechanisms of transverse yarn cracking, inter-yarn debonding, and delamination in a 5-harness satin woven graphite/epoxy composite were modeled using simple mechanistic models. Each of the three models was able to capture the salient features of the woven fabric architecture and also the physics of the damage mechanism. The interaction between the three damage mechanisms was implicitly modeled by including (i) the effect of matrix cracking in the stiffness model for inter-yarn debonding and (ii) the effects of matrix cracking and inter-yarn debonding in stiffness model for delamination. These models were used to determine the effect of the three major damage mechanisms on the laminate stiffness loss during fatigue. The predictions for laminate stiffness loss were compared with tension-tension fatigue test data. By using these damage mechanism models together with interlaminar fatigue delamination growth data (da/dN), it was possible to assess the fatigue life of the woven composite laminate. The fatigue life predictions compared reasonably well with test data. The present fatigue modeling technique should be very useful in designing with woven composite laminates, especially since it can provide estimates of both the fatigue stiffness degradation and the fatigue life.

KEYWORDS

Damage, life, failure mechanism, delamination, matrix cracking, debonding, stiffness degradation, polymer.

INTRODUCTION

Woven polymeric composites are currently being used on several aircraft components. However, there is a lack of fatigue analysis methodology for such woven composites. This analytical capability is critical in the design of aircraft and aero-engine components. There have been very few investigations in the past on the fatigue damage mechanisms of woven graphite/epoxy composites. In two recent studies, Patel and Case [1, 2] investigated the microcracking response, residual strength, fiber-matrix debonding, and dynamic stiffness loss response under fatigue of a woven graphite/epoxy composite. There have been even fewer efforts in the past on the modeling of fatigue damage mechanisms of a woven composite. Kumar and Talreja [3] recently presented a damage mechanics based model for predicting the stiffness properties of a woven composite with transverse cracking. Naik, *et al.* [4] presented simple mechanism-based models to characterize the major fatigue damage mechanisms of a woven graphite/epoxy composite.

In the present study, the three major damage mechanisms of transverse yarn cracking, inter-yarn debonding, and delamination in a 5-harness satin woven graphite/epoxy composite were modeled using simple mechanistic models. Each of the three models was able to capture the salient features of the woven fabric architecture and also the physics of the fatigue damage mechanism. The interaction between the three damage mechanisms was implicitly modeled by including (i) the effect of matrix cracking in the stiffness model for inter-yarn debonding and (ii) the effects of matrix cracking and inter-yarn debonding in stiffness model for delamination. These models were used to determine the effect of the three major damage mechanisms on the laminate stiffness loss during fatigue. The predictions for laminate stiffness loss were compared with test data. By using these damage mechanism models together with interlaminar fatigue delamination growth curves (da/dN), it was possible to assess the fatigue life of the woven composite laminate. Fatigue life predictions using the present analysis compared reasonably well with test data.

MATERIAL, TESTING, AND FATIGUE DAMAGE MECHANISMS

The material used in this study was AS4/PR500 graphite/epoxy woven composite. A 5-harness satin woven fabric (5HS) constructed using 6k (6000 filaments) yarns of the AS4 fibers at a spacing of 4.724 yarns/cm (12 yarns per inch) was used for each of the plies. The laminate consisted of 8 warp-aligned plies and was fabricated using resin transfer molding (RTM). The nominal thickness of the panels was 2.896 mm (0.114 inch) and the composite fiber volume fraction was 55%. Fatigue testing [1, 2] was performed at 10 Hz and an R-ratio of 0.1. The major initial damage mechanisms were transverse yarn cracking followed by debonding at the yarn cross-over regions (see Fig. 1). Such inter-yarn debonding at the yarn cross-over regions was termed as “meta-delamination” by earlier researchers [1, 2]. This initial damage was followed by delamination, which emanated from the tips of the transverse yarn cracks and also the specimen edges.

MODELING OF FATIGUE DAMAGE MECHANISMS AND FATIGUE LIFE

The transverse yarn cracking in the 5HS woven composite was modeled by considering the repeating unit cell for the 5HS weave architecture (Fig. 2). This unit cell was further idealized as a [0/90] laminate [4]. The inter-yarn debonding failure mechanism was modeled by representing the debonded regions in the repeating pattern of the 5HS weave by an “equivalent” debonded region (Fig. 3). The edge delamination observed during fatigue was modeled using the classic O’Brien model [5] with appropriate extensions to a woven composite laminate.

Transverse Yarn Cracking Model

The transverse yarn cracking model in Fig. 2 was idealized as a [0/90] laminate in which the stiffness, E_1, of the 0-deg layer was calculated as the “effective” stiffness of the warp yarns after accounting for yarn undulations. The stiffness of the 90-deg layer, E_2, was computed as the “effective” combined stiffness of the transverse yarns and the interstitial matrix. The normalized stiffness, E_{mN}/E_o, for a [0/90] laminate with transverse cracks is given by [4]:

$$\frac{E_{mN}}{E_o} = \frac{\left[\dfrac{\sigma_{tr}}{\sigma_a} - \dfrac{E_2}{E_o}\right]}{\left[\dfrac{\sigma_{tr}}{\sigma_a}\left(\dfrac{5}{3}\dfrac{E_2}{E_1}+1\right) - \dfrac{E_2}{E_o}\left(\dfrac{E_2}{E_1}+1\right)\right]} \tag{1}$$

where E_{mN} is the laminate longitudinal stiffness after N cycles, E_o is the undamaged laminate longitudinal stiffness, σ_{tr}, is the maximum cyclic transverse stress in the transverse yarns between adjacent transverse cracks, and, σ_a, is the maximum applied cyclic stress. Equation (1) was based on a simplified form of the shear-lag expressions derived by Lee and Daniel [6] for a [0/90] composite laminate. It was shown in Ref. [4] that for different applied stresses, σ_a, the variation of, (σ_{tr}/σ_a), as a function of fatigue cycles could be represented by a single curve. This empirical curve was given by [4]:

$$\frac{\sigma_{tr}}{\sigma_a} = A\,\mathrm{N}^{-d} \tag{2}$$

Using Eqs. (1) and (2), it is possible to determine the variation of the normalized stiffness, E_{mN}/E_o, for a transversely cracked woven composite laminate as a function of fatigue cycles.

Inter-Yarn Debonding or "Meta-Delamination" Model

As shown in Fig. 1, the woven composite exhibits inter-yarn debonding at the yarn crossover regions. This damage mechanism is unique to woven fabric- reinforced composites. A simple model was used to account for the longitudinal stiffness loss resulting from this damage mechanism. Figure 3 depicts an equivalent inter-yarn debonding model that was used to represent the debonding at the crossover regions in the repeating unit cell (of length, L) of a 5-harness satin weave composite. By assuming that the composite displacements are the sum of the displacements [5] in the undamaged region of length, L-a, and the locally debonded region of length, a, an expression can be derived for the stiffness, E_{md}, of the locally debonded composite as:

$$\frac{1}{E_{md}} = \frac{(1-a/L)}{E_{mn}} + \frac{(a/L)}{E_{LD}} \qquad \text{i.e.,} \qquad \left(\frac{E_{md}}{E_o}\right) = \frac{(E_{LD}/E_o)(E_{mn}/E_o)}{\frac{E_{mn}}{E_o}\left(\frac{1}{n}\right) + \frac{E_{LD}}{E_o}\left(1-\frac{1}{n}\right)} \tag{3}$$

where, E_{mN}/E_o, is the normalized stiffness loss due to transverse cracking (given by Eq. (1)) and, E_{LD}, is the stiffness of the locally delaminated region. In the present analysis, E_{LD}, was assumed to be $E_1/2$, where E_1 is the equivalent longitudinal stiffness of the warp yarns. For a woven composite with a "*n* x *n*" repeating weave pattern, where *n* fill yarns interlace with *n* warp yarns (in the unit cell), the ratio (a/L) is given by (1/*n*). For the 5-harness satin weave, (a/L) = (1/5). Note that Eq. (3) includes the effect of the transverse yarn cracking given by the, E_{mN}/E_o, terms.

Edge Delamination Model for a Woven Composite

The edge delamination damage mechanism was modeled, in the present study, using an analysis similar to O'Brien's [5] edge delamination model for laminated composites. The longitudinal stiffness of the edge delaminated laminate in Fig. 4, can be derived by assuming that the total load on the laminate is the sum of the loads in the edge delaminated region (of width, c) and the rest of the laminate (of width, 2b-2c). The longitudinal laminate stiffness, E_{ed}, can be derived as:

$$E_{ed} = A_D E^* + (1-A_D)E_{md} \qquad ; \; A_D = (m\,c/b) \tag{4}$$

where, A_D, is the delaminated area fraction defined as the ratio of edge delaminated area to the total surface area of the laminate. It is assumed that edge delaminations initiate and grow equally at all ply interfaces in the woven composite. The symbol, m, represents the number of sublaminates formed by these delaminations. For the 8-ply laminate considered here, m = 7. The delamination length, c, represents the length of the delaminations at each of the, m, ply interfaces. It is also assumed that the delamination lengths, c, on both edges of the laminate are equal. E^* is the stiffness of the delaminated region. In the present study E^* was assumed as $E_1/2$, where E_1 is the equivalent longitudinal stiffness of the warp yarns. E_{md} is the stiffness of the laminate which has no edge delamination, and is given by Eq. (3). This region contains damage in the form of inter-yarn debonding and matrix cracking.

Stiffness Degradation and Fatigue Life Model

The stiffness evolution and fatigue life were determined using an empirical growth law for the delamination growth rate. The delamination growth rate, $(dc/dN)_{ed}$, was assumed to follow a power law relationship as:

$$\left(\frac{dc}{dN}\right)_{ed} = B\,G_{ed}^{\beta} \tag{5}$$

where, G_{ed}, is the strain energy release rate and the parameters, B, and, β, are determined using delamination growth tests. The strain energy release rate, G_{ed}, for edge delamination was also derived using an extension of O'Brien's [5] model as:

$$G_{ed} = \frac{t\sigma_a^2}{2mE_o}\left(\frac{E_{md}}{E_o} - \frac{E^*}{E_o}\right) \quad (6)$$

where, t, is the laminate thickness (Fig. 3), σ_a is the maximum applied cyclic stress, and (E_{md}/E_o) is computed using Eq. (3). Note that Eq. (6) is a function of (E_{md}/E_o) which is a function of the evolution of transverse yarn cracking. If we assume that the transverse yarn cracking essentially reaches a plateau and does not propagate after the onset of delamination, then (E_{md}/E_o) can be replaced by it's value at delamination onset, $(E_{md}/E_o)_{do}$, and G_{ed} will remain constant throughout the delamination propagation stage.

Equation (5) was integrated to give an expression for the delamination length, c, in terms of, G_{ed}. The unknown constant of integration was determined from the condition that $c \approx 0$ when $N = N_{do}$, where N_{do} is the cycles required for edge delamination onset. This resulted in the following expression for the delamination length, c:

$$c = B\, G_{ed}^{\beta}(N - N_{do}) \quad (7)$$

The variation of the laminate normalized stiffness, (E_{ed}/E_o), can then be expressed using Eqs. (4) and (7) as:

$$\frac{E_{ed}}{E_o} = \frac{mBG_{ed}^{\beta}(N - N_{do})}{b}\left(\frac{E^*}{E_o} - \left(\frac{E_{md}}{E_o}\right)_{do}\right) + \left(\frac{E_{md}}{E_o}\right)_{do} \quad (8)$$

Note that Eq. (8) includes the effects of both transverse yarn cracking (until delamination onset) and inter-yarn debonding.

The criterion used in the present analysis for fatigue failure was based on the maximum cyclic strain, ε_a, in the laminate and was given by:

$$\varepsilon_a = \frac{\sigma_a}{E_{ed}} \geq \varepsilon_{cr} \quad (9)$$

Using Eqs. (8) and (9) the fatigue life of a woven composite laminate can be expressed as:

$$N = N_{do} + \frac{b}{mBG_{ed}^{\beta}\left((E^*/E_o) - (E_{md}/E_o)_{do}\right)}\left(\frac{\sigma_a}{\varepsilon_{cr}E_o} - \left(\frac{E_{md}}{E_o}\right)_{do}\right) \quad (10)$$

RESULTS AND DISCUSSION

The models described in the previous section were used to analyze the stiffness degradation and the fatigue life of the AS4/PR500, 5HS composite. The effective axial stiffness of the undulating yarns, E_l = 119.3 GPa, was calculated using the rule of mixtures and the measured [1, 2] value of E_o = 64.12 GPa and the estimated value of E_2 = 9.03 GPa. E_2 was estimated using constituent graphite fiber and epoxy matrix properties along with micromechanics and textile mechanics analyses described in Refs. [7, 8]. The parameters, A and d, in Eq. (2) were determined in Ref. [4] as, 0.0883 and 0.0083, respectively. The parameter, β = 5.25, in Eq. (5) was obtained from Ref. [9] which tested a similar RTM graphite/epoxy composite under mode II fracture conditions. The parameter, $B = 8.3\text{x}10^{-18}$, in Eq. (5) was selected to match the average measured stiffness degradation rate at 70% of ultimate tension strength (UTS). The value of, N_{do}, was estimated using an initial crack size of 0.3 mm in Eq. (5). The predicted stiffness degradation using Eq. (9) is shown in Fig. (5) and it correlates reasonably well with the measured stiffness degradation.

The critical maximum cyclic strain, ε_{cr}, under fatigue was estimated using $N = N_{do}$ in Eq. (10) for a maximum fatigue cyclic stress of 80% UTS. It was assumed that at this high stress level delaminations would become unstable as soon as they were initiated. Figure 6 shows that the predicted fatigue life (S-N curve) compares reasonably well with test data.

SUMMARY

Simple mechanism-based models were developed for the effects of matrix cracking, inter-yarn debonding, and delamination on the longitudinal stiffness of a woven composite. Using these models it was possible to predict both the stiffness loss and the life of a woven AS4/PR500, 5HS graphite/epoxy composite at room temperature under tension-tension fatigue loading. The present analysis predicted the trends in the stiffness degradation and the fatigue life reasonably well. The present fatigue modeling technique should be very useful in designing with woven composite laminates, especially since it can provide estimates of both the fatigue stiffness degradation and the fatigue life.

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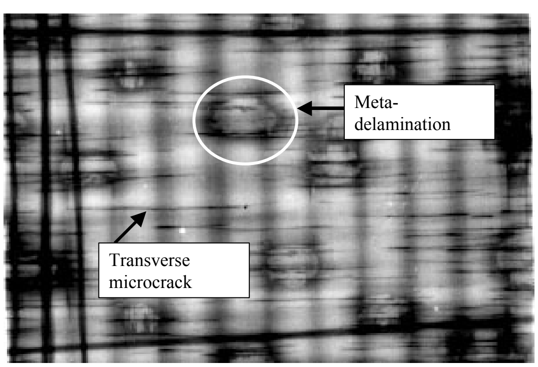

Figure 1: Radiograph showing the transverse yarn cracking and 'meta-delamination' damage.

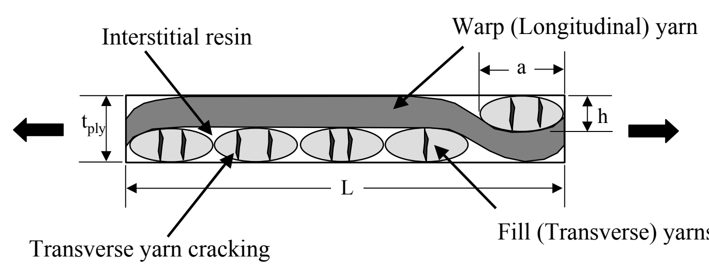

Figure 2: Transverse yarn cracking model showing repeating unit cell of a 5-harness satin weave ply.

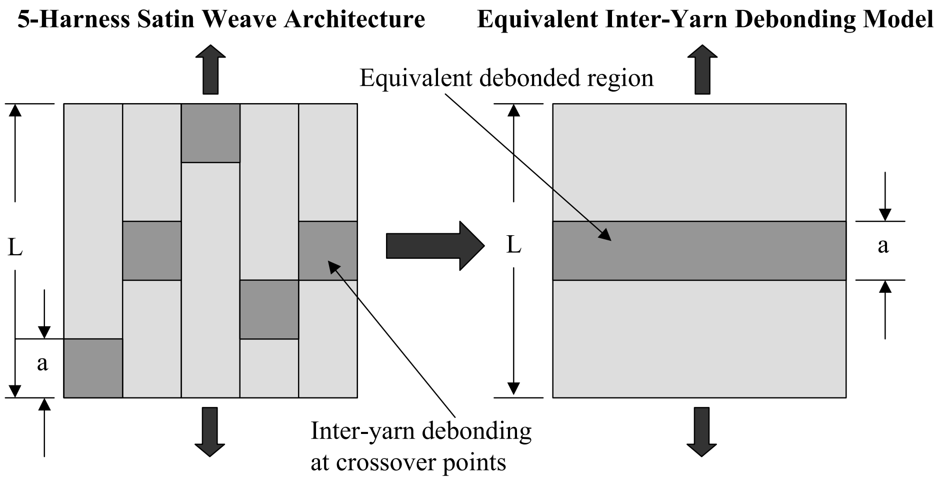

Figure 3: Equivalent inter-yarn debonding model for a 5-harness satin weave composite ply.

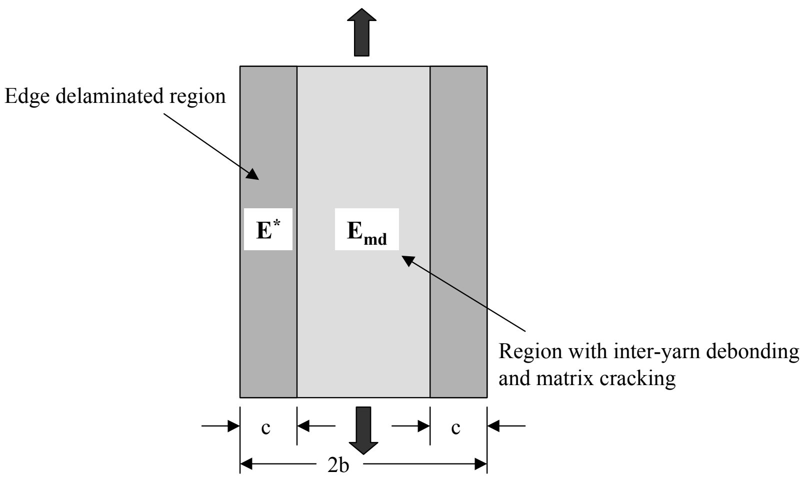

Figure 4: Edge delamination model for a woven composite laminate.

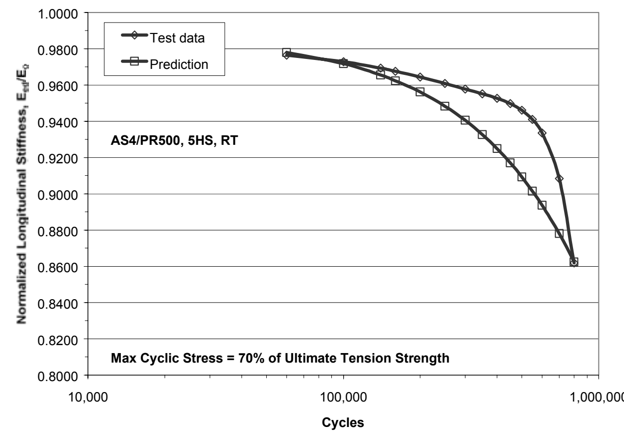

Figure 5: Comparison of predicted and measured normalized stiffness loss during fatigue.

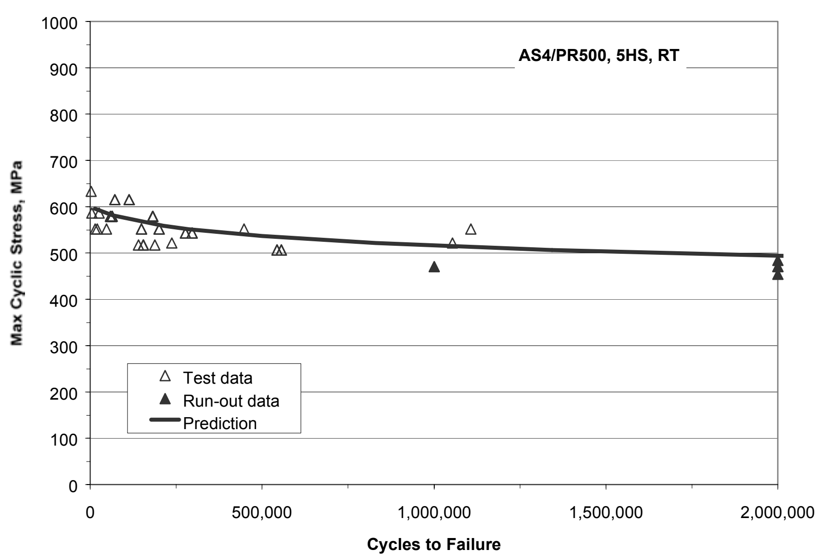

Figure 6: Comparison of predicted fatigue life S-N curve with test data.