Damage state model for fatigue of CFRP

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Abstract. Fatigue is the major failure mode for any structure under cyclic loading. In particular, composite materials exhibit highly complex damage mechanisms and are often overdesigned due to lack of understanding under cyclic loading. Many papers have been written on the modelling of fatigue in fiber reinforced composites. All such models they assumed some internal damage parameter which themselves defined by the mechanical property. However, the growth of these damage parameters are themselves defined by the mechanical property degradation. Hence these fatigue models do not give actual stiffness degradation. In this study, actual 3D microstructural damage in CFRP under cyclic loading was quantitatively measured. Damage micromechanisms viz., fiber breakage, matrix microcracking, debonding, and fiber pull-out were estimated and a model to predict the property degradation with these damage mechanisms (parameters) was developed. Thus, the property degradation in CFRP under cyclic loading was modelled with independently measured damage parameters.

1. Introduction
Carbon Fiber-reinforced composites are increasingly used as structural parts in the fields of aerospace, aviation and transport vehicles for their excellent specific strength and stiffness. Most of these structures are built to be in service for a long time during which they will be subjected to fatigue loads. The strength and stiffness degradation of the composite under fatigue loading is not well understood, which leads to conservative and overdesign of composite structure. Therefore it is necessary to understand how strength and stiffness are degrading under cyclic loading. Many papers have been written on the modelling of fatigue in fiber reinforced composites [1-4]. Degrieck and Van [1] have classified fatigue modelling in three categories as fatigue life models, progressive models, and Phenomenological models. In these models, they assumed some internal damage parameter which themselves defined by the mechanical property. Therefore these fatigue models do not give actual stiffness degradation.

In this paper, actual 3D microstructural damage such as fiber crack, fiber pull-out, fiber/matrix debonding and matrix crack were quantitatively measured. The damage induced due to fatigue loading of unidirectional carbon fiber reinforced polymer (CFRP) composites was quantified using optical microscopy. Finite element analysis (FEA) was used to find effective stiffness of damaged composite and undamaged composite. Quantitatively measured damages were used as input for FEA. Stiffness obtained using FE analysis was compared with experimental results.

2. Experimental Work
An organized experimental study was performed, consisting of tensile and fatigue tests of unidirectional coupons [5]. The coupons were made from AS4 carbon prepreg (carbon fiber)/914C (epoxy resin) with 0.6 volume fraction. As per ASTM 3039, test specimens were prepared, and bidirectional glass/epoxy tabs were glued at their ends. The length and width of the coupons were 250 mm and 15 mm, respectively.
Their nominal thickness was 2.4 mm. The length of the tabs with a thickness of 2.5 mm was 70 mm leaving a gauge length of 110 mm. Static tests were performed under displacement control at a speed of 2 mm/min. Fatigue testing were load control with different stress ratios, R = 0.5 and R = 0.7 (T–T). Interrupted cyclic testing was performed to obtain a different degree of internal damages. Coupons with varying degrees of internal damage were sliced, mounted, and polished for characterization under an optical microscope to quantify damages.

Damage measurement was done by using quantitative stereology. Stereology [6] is a method in which two-dimensional (2D) measurements can obtain quantitative data about three-dimensional (3D) parameters defining the structure from micrograph images. Fiber cracks were calculated in terms of fiber cracks per unit volume, $(N_f V_f)$. It is defined by,

$$ (N_f V_f) = \frac{(N_f A_f)}{H} $$

Where $(N_f A_f)$ is the number of fiber cracks per unit area in $\mu m^2$ and H is the mean caliper diameter in $\mu m$. Fiber/matrix debonding and matrix crack were estimated by measuring surface area per unit volume of debonding and matrix crack, given by the stereological equation:

$$ S_v = 2 I_L $$

Where $S_v$ is the surface area per unit volume in $\mu m^2$ and $I_L$ is the average number of intersection points per unit length of a test line in $\mu m$.

3. Finite element model generation

The finite element analysis usually involves a study of a representative volume element (RVE) of a fiber with a periodic packing sequence. Fiber distribution at the cross-section of the composite lamina is usually quite random [7]. For simplicity, the periodic arrangement of fibers in the micromechanics model was assumed so that RVE can be isolated. The most commonly used periodic sequences of fibers are a square array and hexagonal array, as shown in figure 1(a)-(b). In this study, we used RVE in which fibers are arranged in hexagonal array and load is applied in the fiber direction, as shown in figure 1(c).

![Figure 1. Fiber arrangement in RVE (a) Square array, (b) Hexagonal array (c) Hexagonal fiber array with loading along the fiber direction (L, B and H in $\mu m$)](image)

For this study fibers were arranged in hexagonal pattern on the rectangle such that they did not intersect any boundary of rectangle. The RVE consisted of three phases, namely polymer matrix, carbon fiber and fiber/matrix interface. Elastic model were used for the matrix and fiber/matrix interface. The fiber has a higher modulus along the longitudinal direction compared to the transverse direction. Hence, carbon fibers were modelled as elastic transversely isotropic. Material properties for fiber $E_L = 225$ GPa, $E_T = 15$ GPa, $\nu =0.2$, $G_{LT} = 15$ GPa, $G_{TT} = 7$ GPa and for epoxy $E = 4$ GPa, $\nu =0.35$, $X_T = 75$ MPa, $X_C = 150$MPa and $S = 70$ MPa [8]. Cylindrical fibers were considered with a diameter of 7 $\mu m$. The interface was modelled as hollow cylinder, around the fiber, with thickness of 0.1 $\mu m$. Fiber volume fraction of 0.6 was taken as measured from the specimen [5]. Fiber crack were introduced by assigning very low stiffness value to a row of elements in fiber.
Periodic boundary conditions were applied by using constraint equation to RVE from Barbero [9]. The degree of freedom of each pair of nodes of opposite vertices, edges, and faces of the RVE kinematic constraints are applied. The degree of freedom of nodes and applied strains are variable in these equations. Depending on which position the nodes are -edges, faces, or vertices - a different set of equations must be used to their degrees of freedom to solve compatibility issues between various kinematic constraints.

4. Results and Discussion

The tensile strength and stiffness of unidirectional CFRP were experimentally measured as $1855.3 \pm 125.0$ MPa and $137.5 \pm 4.5$ GPa, respectively. Fatigue testing (till fracture) of coupons was carried out with different load factors. S-N curve was plotted in terms of maximum stress ($\sigma_{\text{max}}$) on the ordinate (Y-axis) and the number of cycles to failure ($N_f$) on the abscissa (X-axis) with semi-log scale. S-N curve obtained from fatigue test for samples loaded along the direction of fiber (referred as $0^\circ$) is shown in figure 2. The endurance limit for $0^\circ$ specimen was about $1480$ MPa i.e. the specimen could sustain more than 1 million load cycles without failure.

The damage progression in the test specimen was measured with the help of optical microscopy and stereology. Optical microscope was used to obtain the micrographs of different samples. Figure 3(a), (b) displays micrographs of $0^\circ$ specimen. Fiber cracks, fiber missing portion and fiber/matrix interface debonding were observed. A typical stress distribution for 7 and 23 fiber RVE without any crack is shown in figure 4.

![Figure 2. S-N curves for unidirectional laminate, $0^\circ$](image)

![Figure 3. Micrographs (a) unidirectional $0^\circ$ specimen: fiber cracks at center of specimen at plan section, (b) $0^\circ$ specimen: fiber missing portion,](image)

The load was applied by increasing the strain along the longitudinal direction until maximum stress, corresponding to the experimental fatigue test, was reached. Stress distribution for 7 fiber RVE, with crack in center fiber, obtained using finite element analysis is shown in figure 5(a), (b). As expected,
axial stress (S11) in the cracked fiber was zero at the crack location. At the crack location, stress from the broken fiber was redistributed to the neighbouring fibres. Stiffness of 7 and 23 fibre RVE composite was not very different and did not change with length of RVE. Hence, it was concluded that the stiffness of composite without any crack was independent of depth of RVE (shown later in figure 6).

Figure 4. Axial stress (S11, GPa) in the fiber without crack for (a) 7, (b) 23 fiber RVE, shear stress (S13, GPa) in the interface for (c) 7, (d) 23 fiber RVE [0 µm (N0)]

Figure 5. (a) Axial stress (S11, GPa), (b) shear stress (S13, GPa) in the fiber with crack for 7 fiber RVE

Finite element simulations carried out with 7 fiber RVE and 227 µm depth for different fiber crack densities were compared with experimentally measured stiffness as shown in figure 7. It was seen that
the stiffness of composite obtained from the finite element simulation was in good agreement with experimental results. However, at R=0.5, there seems to be an outlier that needs further investigation. Thus, a method was established to determine the size of the RVE to predict stiffness reduction in a composite material for a given microstructural damage state and was confirmed with experimental results.

![Figure 6. Stiffness of 7 and 23 fiber RVE](image1)

![Figure 7. Modulus calculated from FEA](image2)

5. Conclusions

Microstructural damage state of a unidirectional CFRP composite was obtained by subjecting it to tension–tension fatigue load for a given number of cycles and stress ratio. Damages were observed in the form of fiber cracking, interface debonding and matrix cracking. Finite element analysis (FEA) was done to develop the methodology to predict the effective stiffness of the CFRP composite for a given damage state. Effective stiffness of composite without crack was found to be independent on RVE depth. Effective stiffness of composite with cracks decreases as the number density of fiber cracks increases. This was found to be in agreement with experimentally observed data.

6. References

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