MICROMECHANICS OF DAMAGE EVOLUTION DURING LONGITUDINAL LOADING IN UD-FRPS WITH VARIABLE STRENGTH DISTRIBUTION ALONG FIBER LENGTH

N. K. Parambil[1], K. M. P. Fathima[2], S. Gururaja[3]

[1]Department of Aerospace Engineering, Indian Institute of Science, Bangalore, India-560012
Email: nithinkp@aero.iisc.ernet.in
[2]Department of Aerospace Engineering, Indian Institute of Science, Bangalore, India-560012
Email: fathima154@gmail.com
[3]Department of Aerospace Engineering, Indian Institute of Science, Bangalore, India-560012
Email: suhasini@aero.iisc.ernet.in, Web Page: http://www.aero.iisc.ernet.in/users/suhasini

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Abstract
Micromechanical damage development during longitudinal loading has been investigated in uni-directional fiber reinforced polymer (UD-FRPs) composites using a numerical framework. Three dimensional repeating unit cell (3D-RUC) representative of UD-FRPs have been generated using a spatially random distribution of continuous fibers. Each fiber is modeled by assigning varying strength distribution using Weibull statistics in line with the weakest link theory. Each fiber is modeled to 'fragment' allowing for multiple fragmentations to occur in multiple fibers. In addition to fiber failure, matrix plasticity and fiber-matrix debonding is allowed to occur. The effective constitutive behavior of the 3D-RUC is obtained using non-linear homogenization principles. Multiple fiber fragmentations are seen to occur upon application of longitudinal loads. Each site of fiber fragmentation is found to trigger other modes of damage; additionally, load sharing behavior has also been captured in the neighboring fibers.

1. Introduction

Prediction of failure in composites is difficult because several damage mechanisms such as matrix cracking, fiber-matrix debonding, fiber breakage, fiber pullout, delamination etc. occur at multiple length scales [1]. The complexity is further enhanced due to the inherent inhomogeneities and randomness associated with spatial arrangement and strength of different constituents of the composite. The heterogeneous structure at the micro level presents unique damage mechanisms that bridge length scales resulting in varied damage mechanisms at the structural level. For a more accurate predictive damage theory, it becomes important to understand the damage mechanisms at different length scales and look at means of bridging the length scales evident in composite structures due to their inherent hierarchical nature. This necessitates the use of advanced computational methods to capture damage initiation and progression in order to accurately predict the material behavior across different length scales.

In the present work, the heterogeneous micro-structure of UD-FRPs has been analyzed using micromechanics via a three dimensional repeating unit cell (3D-RUC) [2–4]. Multiple fiber fragmentations in UD-FRPs due to varying strength distribution among the fibers as well as along the fiber length is of interest in the present work.

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2. Approach

A numerical modeling framework for rapid generation of random micro-structures has been integrated within ABAQUS for 3D-RUC by using python scripting interface. An algorithm to generate multiple fibers with randomly distributed strengths along the length of the fiber embedded in matrix has been developed. Radius of the fiber, fiber volume fraction (V_f) and fiber length are the input parameters to generate the micro-structures. Variation in the strength of fiber along the length has been assigned by partitioning the fiber and assigning a separate strength for each section. Fig. 1 shows the finite element model for the current analysis and consists of matrix, fiber and fiber-matrix interface. 3D-RUC has been meshed using 3D 8-noded linear isoparametric elements (C3D8). Multi-point constraint equations have been adopted to assign periodic boundary conditions (PBCs) for each nodal pair. Table 1 shows the mechanical properties used for fiber and matrix. Single fiber with randomly distributed strengths along the length is studied by varying the fiber length and compared with randomly distributed fiber in the matrix case.

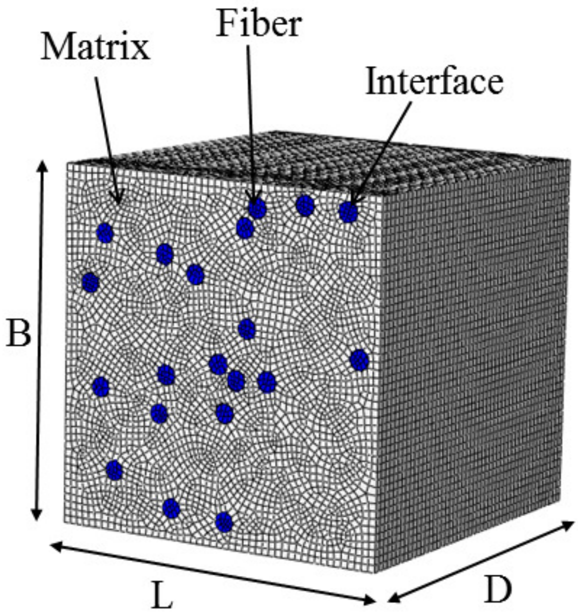

Figure 1. 3D-RUC.

Table 1. Material properties for C-fiber and matrix [5].

	E_{11} (GPa)	E_{22} (GPa)	ν_{12}	ν_{23}	G_{12} (GPa)	G_{23} (GPa)	σ_T (MPa)	σ_Y (MPa)
Carbon fiber	235	14	0.2	0.25	28	5.6	2500	-
Matrix	4.8	-	0.34	-	-	-	-	60

Matrix has been modeled as an elasto-plastic isotropic material. von-Mises yield criterion and isotropic hardening law are used to predict matrix plasticity and plastic flow analysis. The hardening rule was obtained via tabular input of raw data for epoxy resin. User material (UMAT) subroutine is implemented

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Table 2. Properties for the C-fiber/matrix interface [2].

K_n (MPa/m)	t_n (MPa)	t_s(MPa)	G_{Ic} (J/m^2)	G_{IIc} (J/m^2)
10^8	50	70	2	6

in FORTRAN within Abaqus framework to implement the yield criterion and isotropic hardening law. Table 2 shows the properties of fiber-matrix interface used in the present analysis. The interface is modeled using surface based cohesive zone model (CZM). The fiber is partitioned based on mesh size along its length and random strengths are assigned to each of these divisions following a Weibull distribution. Fiber failure is modeled via a UMAT based on maximum stress criterion. Once the criterion for maximum stress reaches in a division, that region of the fiber is assumed to "fail". Fiber failure is simulated by assigning a degradation factor (1%) to the appropriate stiffness coefficient in the fiber region. For the implementation of variation in strength of fiber along its length, two parameter Weibull distribution as shown in Eq. 1 is adopted using scale (σ_o) and shape (m) factors as 2500 MPa and 6 respectively[6].

$$P(\sigma) = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_o}\right)^m\right] \tag{1}$$

3. Results and Discussion

Convergence studies

Prior to obtaining homogenized stress–strain plots for progressive damage analysis of the 3D-RUC, rigorous studies were carried out to determine the mesh size, element type and interface parameters. In particular, the current approach links the fiber sections with varying strength with the mesh size. Thus, it becomes important to have a reasonably small mesh that would negate the effect of mesh size. In addition, the load increment needs to be sufficiently small in order to capture the local load drops that occur due to fiber breakages. It should be noted that the damage parameter introduced to simulate the fiber fracture results in strain localization effects due to localized reduced stiffness of the fiber. Such strain localizations result in increased computational time and often results in convergence issues.

Single fiber 3D-RUC versus randomly distributed fibers 3D-RUC

Damage development in a 3D-RUC with V_f = 5 % case has been detailed in the present work. To begin with, the effect of 3D-RUC size (i.e., length) has been studied. The homogenized stress strain curve obtained for longitudinal loading for varying 'D' for a single fiber 3D-RUC has been shown in Fig. 2. In addition, one case of 3D-RUC with 20 randomly distributed fibers and D=L has been overlaid over the single fiber 3D-RUC results. From Fig. 2 it can be inferred that allowing for multiple fiber fragmentations within a single fiber helps in capturing the longitudinal damage mode more accurately. Beyond D=10L, the homogenized stress-strain curves converge. Using multiple fibers allows for 'local load sharing' to occur thereby replicating the longitudinal damage mechanisms more accurately. Concurrently, the homogenized stress-strain curve for N=20 case with D=L coincide with D=10L single fiber case. In other words, due to local stress redistribution effects, the effective dimensions of the RUC takes a smaller value as compared to a single fiber 3D-RUC.

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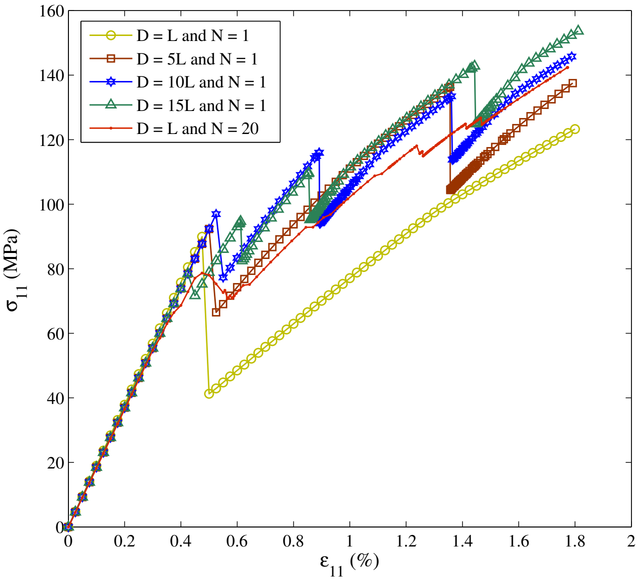


Figure 2. Homogenized stress strain curves for D = L, 5L, 10L (N = 1) and D = L (N = 20) with varying strength along the fiber.

3D-RUC with randomly distributed fibers

Fig. 3 depicts a detailed view of the homogenized stress-strain curve for D=L and N=20 case. As can be seen from the figure, the homogenized stress–strain plot is characterized by repeated load drops upon increasing load levels. Each load drop is indicative of either a single or a collection of fiber sections failing. The fiber sections need not be present in the same fiber. Consequently, the homogenized stress–strain curve depicts a progressive degradation in the overall stiffness with increasing fiber fragmentations. In previous studies wherein the strength was varied across fibers, load drops indicative of fiber failures were witnessed [3]. However, it should be noted that [3] used a single strength for the entire fiber. Thus, as the stress magnitudes reached the strength of a particular fiber, the entire fiber would break without contributing to further load carrying capability of the micro-structure. Since experimental observations have confirmed that multiple fiber breaks do occur, varying strength along the length of the fiber helps in simulating the actual physics of fiber fragmentation in UD-FRPs.

It has also been observed that each fiber fragmentation is accompanied by a localized redistribution of stress or 'local load sharing' as depicted in Fig. 4 (a). Such a localized effect determines the damage progression characteristics in UD-FRPs and proves that progressive damage modeling is inherently dependent on the localized micro-structural attributes. In addition to 'local load sharing' effects, matrix plasticity is also observed in the vicinity of fiber breaks as shown in Fig. 4 (b).

As mentioned earlier, multiple fiber fragmentations that result in observable load drops in the homogenized stress–strain curve are not restricted to a single fiber. Depending on the statistical strength distribution assigned to the entire domain encompassing all the fibers, fiber breaks occur at the 'weakest' regions. Fig. 5 (a) - (c) depict fiber failures corresponding to points A - C, respectively. As can be observed, the fiber failures are occurring in several fibers simultaneously. The progressive breakage of fibers continues to occur upon further load application.

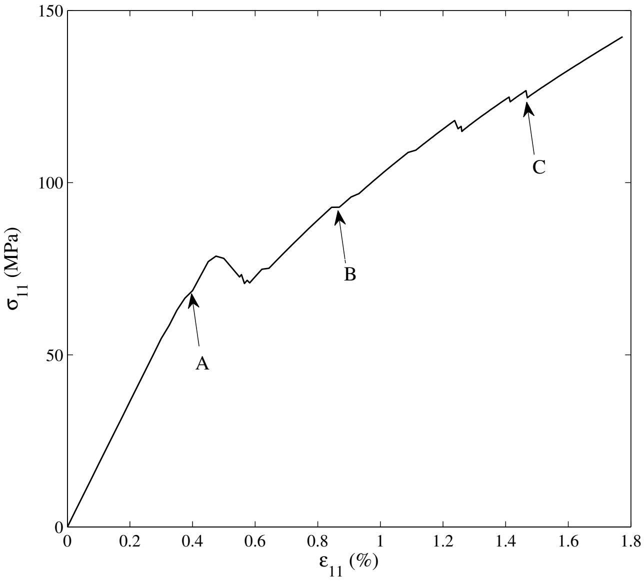
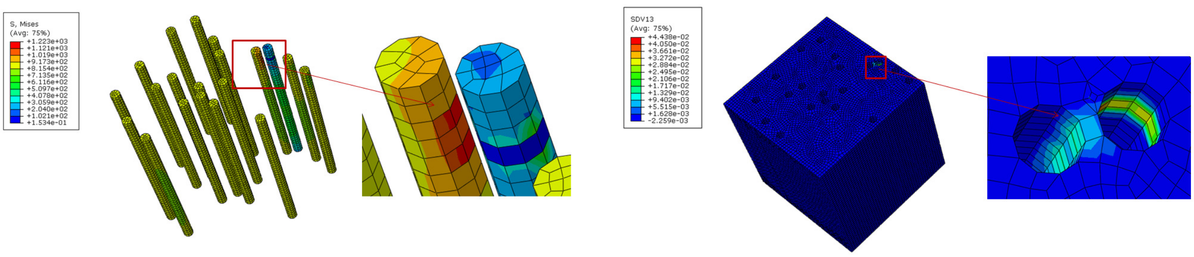
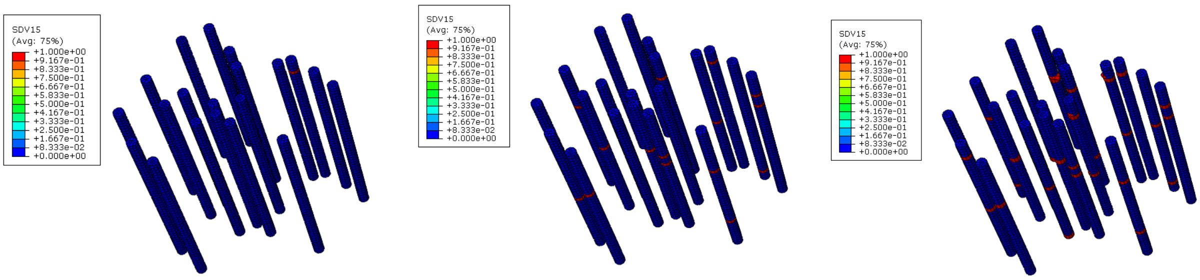


Figure 3. Homogenized stress strain curves for D = L (N = 20) with varying strength along the fiber.



(a) (b)

Figure 4. (a) Local load sharing after first fiber break. (b) Matrix plasticity after first fiber break.



(a) (b) (c)

Figure 5. (a) Failed elements in fiber corresponding to point A (b) Failed elements in fiber corresponding to point B (c) Failed elements in fiber corresponding to point C

4. Conclusions and Future Work

3D-RUC with multiple fibers randomly oriented were modeled to have varying strengths along the fiber length using Weibull statistics. The following conclusions can be drawn:

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1. The current model is able to capture multiple fiber fragmentations that are seen to occur due to varying strength assigned at the start of the analysis.

2. Each fiber break is followed by stress redistribution locally that effects the damage progression characteristics.

3. Matrix plastic strains are seen to occur in the vicinity of fiber breaks. Fiber-matrix debonding onset is also found to occur in some cases.

4. The RUC size required for multiple fibers case is found to be smaller than single-fiber case.

The matrix model needs to be updated allowing for matrix damage to also occur. In the current formulation, since there is no matrix damage occurring, the plastic strains could reach unrealistically high values. The authors are reworking the results with an appropriate matrix cracking model based on smeared crack approach. In addition, the results presented in this work need to be validated with macro-level tests. In order to do that, it is critical to incorporate an approach for multi-scale damage development.

5. Acknowledgments

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