Steady-State Debond Growth Along Broken Fibers in Unidirectional Composites During Cyclic Loading

J. VARNA[1] and A. PUPURS[1,2]

Several regions with different governing failure mechanisms may be distinguished analyzing axial tension-tension cyclic loading of unidirectional (UD) composite. At high loads multiple fiber fracture takes place during the first loading cycle. The relative number of broken fibers depends on the maximum stress and can be estimated assuming that the fiber strength is a statistical property following Weibull distribution. Multiple fiber fracture (fragmentation) is possible because the load is transferred into the broken fiber through the interface. In cyclic loading with constant amplitude we usually assume that fibers do not experience fatigue and all fiber breaks occur during the first cycle. During the following cyclic loading debonds start to grow along the fiber/matrix interface and this is the main mode of damage progression analyzed in this paper. The extensive debonding reduces the load borne by the broken fiber causing new fiber breaks and connecting the multiple fiber breaks, finally leading to catastrophic rupture of the UD composite. Hence, understanding of the debond growth process in fatigue is crucial for fatigue life analysis in this load region.

The debond growth in this paper is treated as an interface crack propagation and analyzed using fracture mechanics concepts (strain energy release rate).The interfacial radial thermal stress which forms during the cool-down to room temperature is compressive due to larger thermal expansion coefficient of the matrix. Additional compressive radial stresses are formed during the tensile axial mechanical loading as a result of different Poisson's ratios. Consequently, there is always a contact between the debonded fiber and the resin and the debond growth is in pure Mode II. The hypothesis used in this paper is that the growth rate of an individual debond is a power function of the strain energy release rate change in one cycle. This hypothesis was validated in [1] analyzing the Single Fiber Fragmentation test (SFF test) results. The debond length was measured in [1] as a function of number of cycles showing that the growth can be described by model based on power law. The material parameters in this law were determined by fitting.

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[1]Lulea University of Technology, Sweden
[2]Swerea SICOMP, Sweden

The objective of this paper is to use the identified power law for the interface failure to simulate debond growth from fiber break in a UD composite made of the same material system. The first step towards this goal is the strain energy release rate calculation. Its value depends on the fiber content and on constituent properties. Several numerical routines related to FEM stress solutions are available for G_{II} calculation (J-integral, VCCT etc.) and are used in this study. The accuracy is evaluated using an analytical model for steady-state debond growth in UD composite.

In the model which is solved numerically as well as analytically the real composite morphology is simplified considering an axisymmetric configuration consisting of three phases. In the model shown in Fig 1 the broken fiber is surrounded by resin and embedded in the effective composite with elastic constants calculated using the Hashin's CCA model and Christensen's generalized self-consistent scheme [2-3].

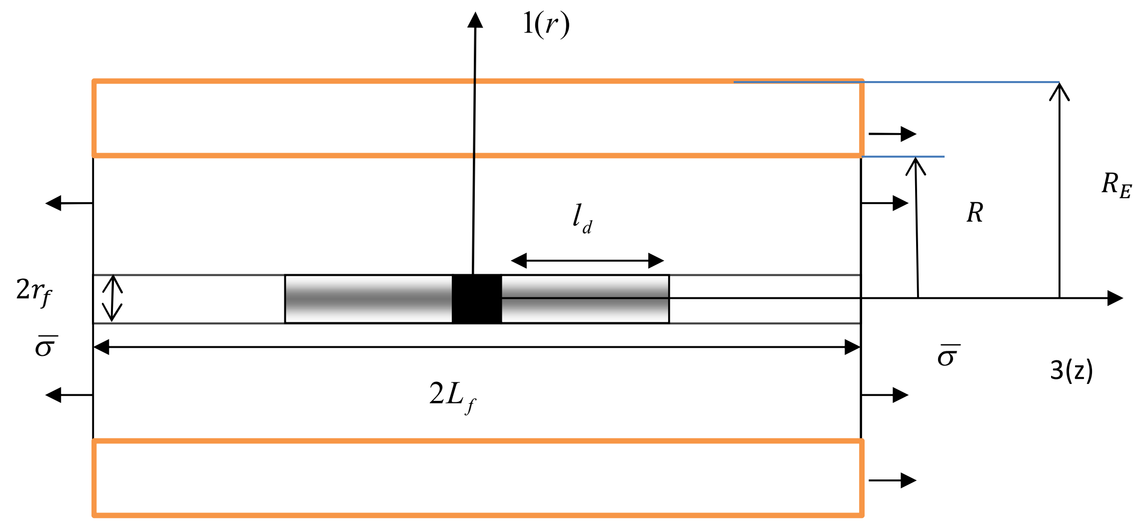

Figure 1. Schematic showing of the 3-phase model with broken and partially debonded fiber.

The analytical solution for the energy release rate during steady-state debond growth was obtained based on consideration that the change of the potential energy when debond grows by dl_d is because a bonded element of the composite of this length is replaced by debonded element of the same length. The obtained expression is a quadratic form with respect to the mechanical strain and the temperature change

$$G_{II} = \frac{E_3^f r_f}{4}\left[k_m^\infty \varepsilon_{mech} + k_{th}^\infty\left(\alpha_3^C - \alpha_3^f\right)\Delta T\right]^2 \qquad (1)$$

Parameters k_m^∞ and k_{th}^∞ very weakly depend on fiber content and phase properties. The model is applicable for a finite outer radius of the cylinder assembly. The latter is especially important for "calibrating" the used numerical routines where modeling of infinite regions is always "troublesome". Single fiber composite without and with coating are considered as particular cases of the model. The limits of applicability of the steady-state solutions are analyzed.

The obtained expressions for G_{II} are used to simulate the debond growth under thermo-mechanical cyclic loading for a wide range of geometrical and elastic parameters

References

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