Composites Part A 109 (2018) 31–47

Contents lists available at ScienceDirect

Composites Part A

journal homepage: www.elsevier.com/locate/compositesa

Uniaxial strength of a composite array of overlaid and aligned prepreg platelets

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ARTICLE INFO

Keywords:
A. Discontinuous reinforcement
B. Strength
C. Damage mechanics
C. Cohesive interface modeling
Platelet

ABSTRACT

The tensile strength of a discontinuous composite system consisting of aligned, unidirectional prepreg platelets is predicted by performing progressive damage analyses in a periodic representative volume element. Interlaminar and in-plane damage mechanisms are combined to yield failure characteristics of the meso-structure. The length-to-thickness ratio of the platelet was found to be the primary variable for control of system strength and failure mode. A critical platelet aspect ratio was determined as that ratio wherein system strength is maximized. Further, composite strength variability was shown to be vary inversely with aspect ratio, while attaining a minimum at the critical aspect ratio.

1. Introduction

Formability and structural characteristics of a fiber-reinforced composite define the possible application for the material. Conventional advanced composite materials consist of multi-axial laminates constructed of lamina of collimated, continuous fibers (CF) pre-impregnated with polymeric matrices. The composite lamina preform is termed “prepreg”. However, complex three-dimensional geometries often cannot be efficiently fabricated as continuous fiber laminates. Yet well dispersed, short fiber molding of these geometries does not yield the superior structural performance of CF systems since fiber length and volume fraction are significantly lower than that of the CF systems. Recently, a modified material form has been introduced that provides for controlled fiber length and fiber volume fractions in the range of 0.5–0.6. These materials are fabricated by transforming CF prepreg tape, through a slitting and cutting procedure, into platelets with a prescribed length, L_p, and width, w_p, while the platelet thickness, t_p, is the prepreg tape thickness. These platelets are then compression or transfer molded into complex geometries appropriate for structural elements. Application of a prepreg platelet-molded composite requires basic knowledge of its performance. Effective/macroscopic properties of a heterogeneous composite system emerge from the complex collective response of the interacting phases, which depends on the material structure and the local properties of each constituent phase. The material structure is a collective arrangement of the phases at the next scale above that of an individual phase. The structure is characterized [1] by the geometrical arrangement of constituents in space (known as material morphology), proportions (fractions) and shapes of the constituent phases. A systematic knowledge of the material structure-property relationship [2] is needed to understand the origins of apparent properties from the material structure and to achieve the desired combination of properties.

Meso-scale morphology is dominant for the properties of a prepreg platelet-molded composite system, meaning the scale where individual platelets are distinguishable. A composite system of platelets fabricated from unidirectional (UD) CF prepreg is a hierarchical system with two levels of recognized scale. As pointed out by Lakes [3], a structure may be present on many scales, but the largest structural element scale controls the effective response of the material system. When continuous fibers are arranged in a collimated, high fiber volume fraction geometry such as in a CF prepreg and that system is cut into platelets that contain fibers of identical length, individual fibers may not be expected to control system strength. Rather, the properties of a platelet based composite are determined by the platelet-scale heterogeneities. Therefore, it is the morphology dependent three dimensional platelet-to-platelet stress transfer governs the failure mechanisms and, consequently, the effective composite strength.

The geometric meso-scale of the platelet composite can be irregular and disordered, having platelets arranged in “random” and varying patterns at various orientations with respect to one another in a semi-laminated manner, as schematically shown in Fig. 1. Irregular disordered meso-structures resulting from uncontrolled platelet deposition and further molding are complex and both property measurements and predictions have shown their large variations [4–13]. The primary

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https://doi.org/10.1016/j.compositesa.2018.02.032
Received 22 October 2017; Received in revised form 18 February 2018; Accepted 22 February 2018
Available online 24 February 2018
1359-835X/

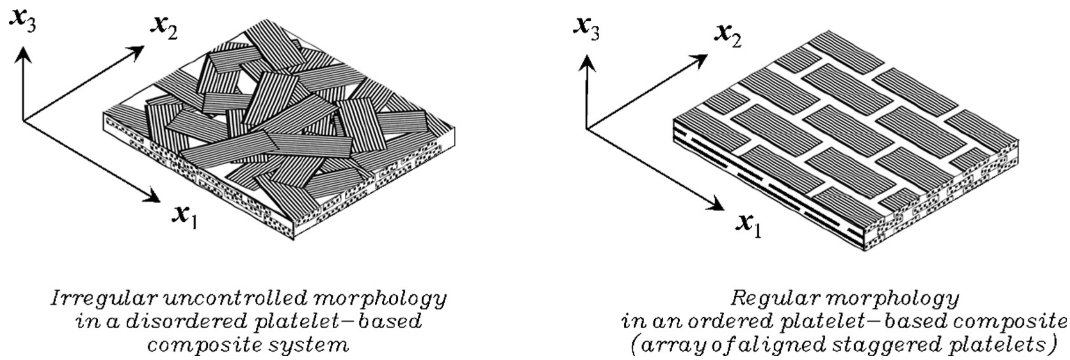

Fig. 1. Schematics of an irregular and regular morphologies of a platelet-based composite system.

observations from the previous studies were that (a) the strength of a platelet-molded material system increased with platelet length (L_p) for a constant thickness (t_p) [4,5,7], (b) the failure was observed to be either platelet pullout or platelet split or rupture, and (c) thinner tape allowed for the improved effective properties [11,12]. Large variability in the experimental data was suggested [14] to be caused by the non-deterministic distribution of arrangement and overlap lengths of platelets.

A composite system with regular morphology must have some repeatable pattern for elements accommodation in space. For instance, all platelets can be aligned and staggered in a certain manner to create a regular morphology, as shown in Fig. 1. Regular morphologies can be engineered, meaning achieved with a specific manufacturing procedure. Simpler geometrical arrangement of platelets defines a "simpler morphology", which actually corresponds to a more ordered composite system, or a structure of a superior hierarchical organization. Ordered system morphology grants superior effective performance characteristics. Besides, if regular morphologies can be manufactured, they represent independent composite systems, which require their own computational predictive models.

In the present work, the authors examine a simple geometry of a meso-structure with many platelets in order to identify stress transfer and strengths as a function of meso-structure geometry (morphology) and platelet aspect ratio in the absence of orientation disorder. An idealized strictly periodic system of aligned staggered prepreg platelets is herein considered. A simple morphology may not be directly useful for quantitative predictions of the effective properties of more complex morphologies but it can provide an insight, qualitative understanding and easier interpretation of common phenomena responsible for the effective performance of various types of morphologies. This work thereby provides the necessary foundation to study the structure-property relationship in more complex irregular and stochastic meso-structures wherein platelet fiber orientation and overlap geometries are more typical of systems resulting from uncontrolled deposition and molding.

Natural [15] and engineered discontinuous composite systems of layered and staggered platelets made of different materials were previously studied for elastic response [16–20] and ultimate strength prediction, based on simplified stress analysis [21–24] or progressive failure analysis (PFA) [25–30]. In these systems, platelets (also termed bricks, strands, flakes, or chips by different authors) were separated by adhesive layers (matrix, mortar, resin). Predictive models for such material systems relate the composite morphology, constituent properties, and platelet geometry to the macroscopic mechanical response of a composite for the purpose of decision making on material selection and processing limits. Both models from [26,27] gave insight to the deformation and failure of platelet arrayed composites, though with limitations on predictive capabilities from inherent assumptions. Models from Refs. [26,27] were plane stress and shear-lag based, implying there were no interlaminar peel stresses allowed at the platelet-to-platelet interfaces, the mismatch in Poisson's ratio between platelet and adhesive layer was not accounted for, besides the platelets were considered isotropic. The authors of [25,28–30] assumed that platelets could not experience breakage and excluded such failure mode from their model.

The focus of this paper is to develop a comprehensive computational model to quantify the structure-property relationship in a composite system of overlaid and aligned prepreg platelets under uniform uniaxial tensile loading in the displacement control. The sub-scale modeling was used for the analysis of three-dimensional local stress transfer and damaged deformation to failure in the composite system. The direct computational homogenization [31,32] was used to yield the effective composite stress at any loading increment. A strictly periodic meso-scale geometry was considered so that a unit cell could exist to adequately represent the heterogeneity of the system. A unit cell was chosen as a representative volume element (RVE) [33] thus making the periodic boundary conditions appropriate to the RVE. The direct finite element method was used to analyze the RVE in ABAQUS/Standard (Implicit). A continuum damage mechanics model for the orthotropic platelet damage modes was coupled with a cohesive zone model at the inter-platelet planes to capture the disbonding between platelets and thereby address the two competing failure mechanisms in the system. The study of the structure-property relationships in the platelet-arrayed composite system revealed that a *"critical platelet length-to-thickness ratio" for the chosen composite morphology* exists to maximize the effective composite strength. This dimensionless parameter is shown to control the failure modes and, consequently, attainable macroscopic composite strength. Variability in morphology of a platelet-based composite is shown to control the strength variability for smaller length-to-thickness platelet aspect ratio. The results also suggest that strength variability caused by meso-morphology in a platelet-based composite system can be mitigated by increasing the platelet length-to-thickness ratio.

2. RVE-based computational model for the progressive failure analysis in a platelet-arrayed composite

2.1. Assumptions for the failure analysis of an array of aligned platelets

Three primary assumptions are employed in this work for the progressive failure analysis in a platelet-arrayed composite system: (i) geometrical idealization of platelet arrangement, i.e. composite heterogeneous meso-scale morphology; (ii) idealization of stress-carrying capacity of the composite elements; (iii) idealization of elementary damage events in the composite system.

The composite system is a collection of UD CF prepreg platelets that have been systematically arranged. It is assumed that platelets are laid side by side and parallel to one another in strictly periodic, but staggered planar arrays with their length direction (coincident with the fiber, or the "*1*"-preferential direction) along the global x_1-direction. Thin matrix layers are assumed to separate the platelets in the thickness direction, x_3. The (x_1x_2)-planar arrays are organized to replicate in every other layer through the stack thickness direction (x_3). Perfect