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EXPLORING TENSILE STRENGTH UNCERTAINTY IN DISCONTINUOUS PREPREG PLATELET MOLDED COMPOSITES CONSIDERING PLATELET SHAPE AND SIZE STATISTICAL DISTRIBUTIONS

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ABSTRACT

A meso-scale computational model is developed to quantitatively compare effective tensile properties of compression molded discontinuous, long fiber composites produced from prepreg tape edge trim (TET) to pristine molding compounds. TET is a by-product of the unidirectional prepreg tape manufacturing process, offering both the potential for valorization and sustainable management of production waste. During the manufacturing of prepreg tape, the tape edge typically exhibits out-of-spec variations for thickness and resin content and thus must be removed by trimming prior to tape rolling. Transforming TET into discontinuous fiber chips (platelets) enables its use as a compression molding compound, eliminating the need to dispose of high-performance constituent material through environmentally harmful methods such as landfilling or incineration. The TET chopping operation produces trapezoidal platelets of varying sizes and shapes. In contrast, the pristine molding compounds can be uniformly square. In both cases, the subsequent compression molding process results in a composite system with a random distribution of platelet overlap and fiber orientation. The statistical variability of local meso-structure translates into uncertainty for mechanical properties of the molded composite. In the current state of the presented work, virtual numerical analysis was used to achieve the primary objective of quantification via statistical means differences in tensile properties between components made from uniform shapes (pristine material) or a variable size distribution (TET). Additionally, the study explored how variations in the distribution of platelet length between trapezoidal and square chips influence the probability distribution of effective mechanical properties, notably strength. Continuum damage mechanics and cohesive zone modeling were used to describe the interacting local meso-scale failure mechanisms.

1 INTRODUCTION

During the manufacturing of thermoplastic prepregs, the material at the tape edge typically exhibits out-of-spec variations in both thickness and resin content, and therefore, it is trimmed prior to tape rolling. The waste product, herein known as tape edge trim (TET), is a discontinuous long fiber composite that can be compression molded. Similar products exist as commercially available bulk molding compounds such as chopped pre-preg molding compound. Individual platelets (also known as “strands”, “chips” or “chopped prepregs”) in TET compounds are distinguishable, indicating a meso-scale heterogeneous structure. Herein, the term platelets will be used to describe a meso-scale building block of TET compounds. TET platelets are the byproduct of a chopping process which minimizes the volume of TET stored before disposal. Smith et al. determined that unlike most commercially available molding compounds which are typically uniformly rectangular or square, TET platelets taken from a prepreg line have a broad distribution of geometrical dimensions [2] [3]. The platelet length-to-thickness ratio affects the tensile properties of PPMC at the structural level and potentially, a large distribution of geometries could result in further variability [2]. The presented study examines the progressive failure analysis (PFA) of a 15.4 cm by 2.54 cm (6 inch by 1 inch) coupon with an explicitly modeled meso-morphology. The purpose of the following work is to present a general overview of a computational model that allows for the quantification of the resulting uncertainty in effective tensile properties considering the following cases 1) uniform square platelets of 0.5 by 0.5 inch 2) trapezoidal platelets with variable dimensions taken from statistical distributions found through experimental measurements of chopped TET. Numerical modeling demonstrated that coupons of trapezoidal platelets had statistically different strengths/stiffness compared to coupons with squares.

2 3D MESOSTRUCTURE GENERATION ALGORITHM

This section will introduce the algorithm used to generate the platelets which make up the FE mesh of virtual tensile coupons. Prepreg platelet molded compounds (PPMC) exhibit structures where the platelets (and hence the fibers) can have random orientation angles with respect to the loading direction whilst remaining "flat", that is in plane with the coupon mold surface. Therefore, randomly oriented PPMC can be modeled as a continuum in (x_1, x_2, x_3) space with sub-domains assigned local coordinate systems (1, 2, 3) to represent randomly aligned stacked platelets. Empirical measurements of platelet geometry were taken by image analysis with ImageJ [2]. Figure 1a shows a histogram of the statistical distribution of platelet geometrical dimensions (L_p, w_p, α, β) of both empirical measurements and virtual platelets. By randomly sampling platelet dimensions from a continuous Weibull distribution (red curve) which has been fitted to experimental data (solid black), the dimensions of trapezoidal platelets used to generate the virtual coupon (colored wireframe) are independently sampled (Figure 1a). This approach allows for improved model reliability without excessive complexity and computational expenses. As evidenced by the agreement between experimental and virtually generated area distributions shown in Figure 1a, the geometrical parameters of the TET platelets are sufficiently representative of reality.

The virtual TET coupons are generated by sequentially adding platelets to an initially empty deposition domain Ω, through the defined coupon volume and incrementally advanced to the coupon surface until the domain is filled (Figure 1c). The definition of randomly placed platelets considers the parameters: θ, L, W, x_1 and x_2 (See Figure 1b). A platelet can be presented as a continuous object using three dimensional units (voxels) with the same orientation. Figure 1c, shows two platelets with their local material coordinate systems where 1 is platelet fiber direction and 2 is transverse to the platelet fiber direction. To represent the three-dimensional structure of platelet cascading, a voxelized representation is chosen as to allow for the simultaneous generation of a realistic geometry and Finite Element (FE) mesh. The voxelized approach may reflect the homogenized structure of the composite system, if representative of the average property [4]. An example of a generated coupon can be seen in Figure 2.

The compression molding processes involve material consolidation flowing under high temperature and pressure where platelets cascade over the previously deposited ones in a "wavy" like fashion. Further refinement and modification was made to the platelet deposition algorithm as first presented in [5] allowing for more realistic representation of platelet cascading (Figure 1b). The voxelized morphology is converted into a finite-element mesh for Finite Element Analysis (FEA), with each voxel becoming an eight-node brick solid finite element (C3D8 in Abaqus/Standard). The voxel thickness was determined through optical microscopy on the through thickness cross-section of a TET coupon. The thickness of each voxel is equivalent to the physical platelet thickness (100 µm) and the length and widths (L_v) are 0.7 mm.

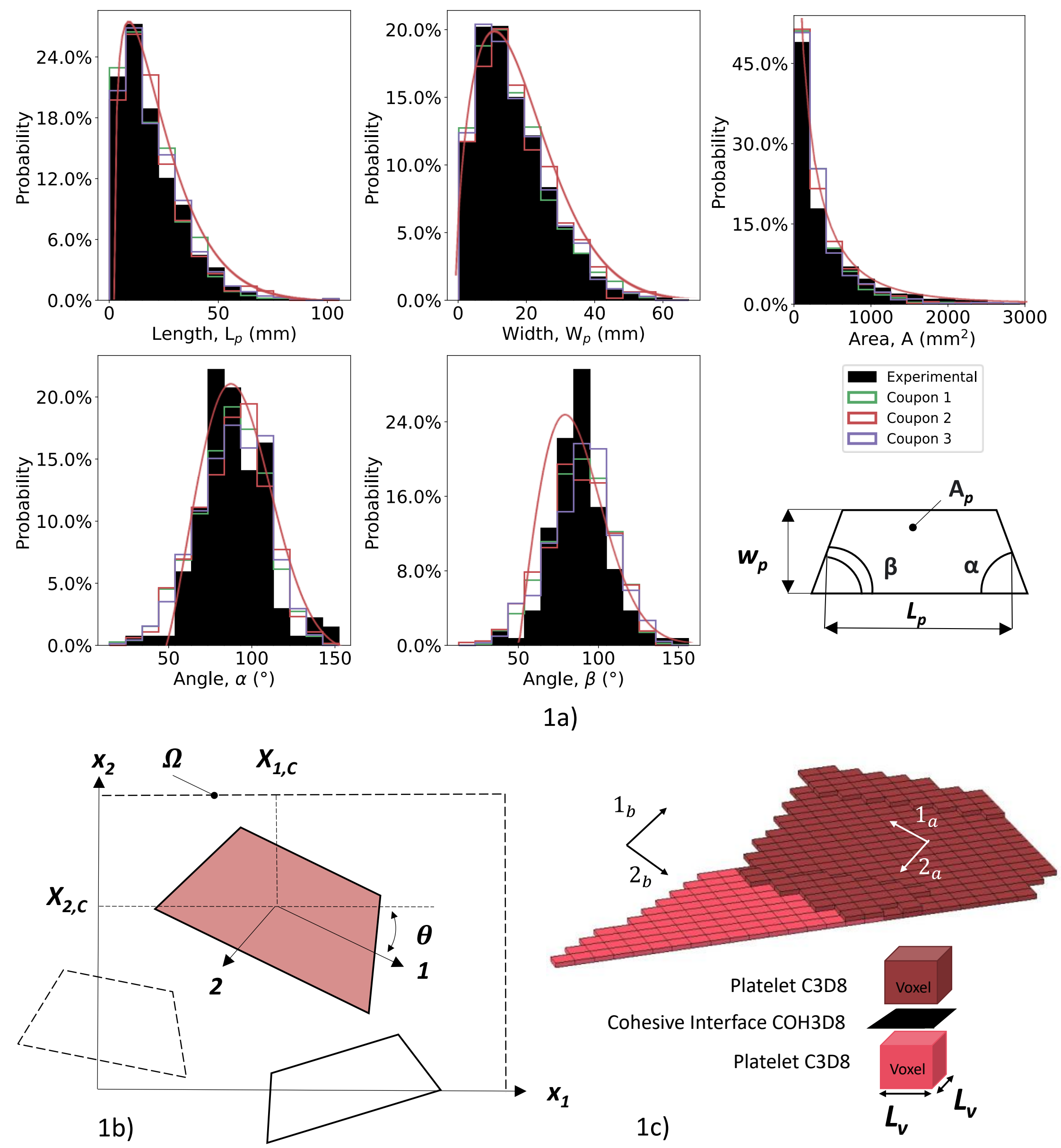

Figure 1. a) Statistical distributions of simulated input parameters (colored wired frames) vs. experimental observations (solid black) used for meso-scale generation with the fitted Weibull distribution. b) Illustration of the local coordinate system with regard to platelet centroids c) Overlapping platelets in a voxelized representation.

All platelet elements are assigned identical homogenized material properties reflective of the parent prepreg tape, and the local orientation is mapped from the geometric representation to the finite elements. Platelets are incorporated into the voxel mesh where distinct colors indicate voxels within the boundaries of a specific platelet (Figure 2). Cohesive elements (COH3D8 in Abaqus/Standard) are inserted at the platelet-to-platelet boundaries which capture out-of-plane interlaminar failures (Figure 1c) [4].

3 PROGRESSIVE FAILURE ANALYSIS OF A TENSILE COUPON

The details of the methodology of the progressive failure analysis are outlined briefly here, further details including the mathematical description and material constants can be found in previous works by Chong et al. [5]. The employed methods for PFA are typical methods used in numerical analysis [6]. The successive evolution of local platelet damage is followed by the ultimate macroscopic failure of the coupon as a whole. PFA is employed because the composition of numerous overlapping platelets in PPMC results in a highly redundant system, such that there is a gradual deterioration from the accumulation of damage before ultimate failure. The primary local meso-scale failures include both platelet in-plane damage which imply the loss of ability to support in-plane stresses (that is fiber splitage or fracture across fibers) and out-of-plane damage (debonding of overlapping platelets) which implies integrity loss in the through thickness direction such that stresses are no longer transmitted between platelets [4]. It follows that multiple local damage sites develop early in the loading history, with a prominent dominant failure site, which is a location of the ultimate macro-crack (visualized as the formation of a dark band) that goes from one side of the coupon to the other resulting in a two-part rupture (Figure 2).

The inter-laminar damage can be described using cohesive zone modeling (CZM) [4]. The presence of a crack implies a distribution of stress transfer which can be modeled as degraded stiffness. The cohesive zone model relates the interfacial stress and opening displacements. A typical approach to the computational representation of damage development is a reduction in stiffness by applying internal damage variables introduced to represent the local platelet mechanical response into the platelet stress-strain constitutive tensor [4]. Continuum damage mechanics (CDM) and the associated constitutive tensors enable complex interactions to be considered among the various meso-scale damage modes occurring in the PPMC coupon during tensile failure. Platelets are considered as an orthotropic homogenized continuum where the in-plane and out-of-plane damage is the result of a tri-axial stress state. The damaged stiffness matrix is determined by relying upon the stiffness components of the undamaged prepreg tape and two damage variables: d_1, d_2. These variables effectively represent a macroscopic crack and correspond to directions in the fiber and transverse to the fiber respectively [4]. Growth of d_i is monotonic from 0 to 1 where $d_i = 0$ represents the initial undamaged state, and $d_i = 1$ a state of complete integrity loss and no further stress transfer. In Figure 2, the undamaged and damaged elements transverse to the fiber (d_2) are identified by the greyscale damage index. The internal state (damage) variable distribution represents the damage progress path. Upon satisfaction of the damage initiation criteria within the defined model framework, further loading decreases the material stiffness coefficients. Assuming linear-brittle fracture, the failure strains are computed from dividing the corresponding strengths over stiffness.

4 RESULTS AND DISCUSSIONS

The PPMC manufacturing process results in probabilistic distributions of orientations and geometries of platelets such that no two coupons are alike and thus will have varied mechanical responses. To explore the probabilistic distribution of effective tensile properties with randomly generated meso-morphologies, ten virtual tensile coupons were generated for platelets of constant square (L_p,W_p = 0.5”) and variable trapezoidal (L_p,W_p = var) platelet geometries respectively. The global length, width and thickness of a coupon are labeled as L, W and t. In terms of boundary conditions applied to the virtual coupon, one edge (x_1=0) is fixed. A displacement u* is applied in the positive x_1 direction at (x_1=L) with all other degrees of freedom constrained to simulate a tensile test. All platelets make an angle with the x_1 loading direction (Figure 3).

In both types of coupon, the platelet structure redistributes the applied load onto undamaged elements, resulting in the formation of multiple precursory damage sites and potential damage progression paths [4]. It follows that multiple local damage sites develop early in the loading history, with a prominent dominant failure site as the site of the ultimate macro-crack (visualized as the formation of a dark band) as shown in Figure 2.

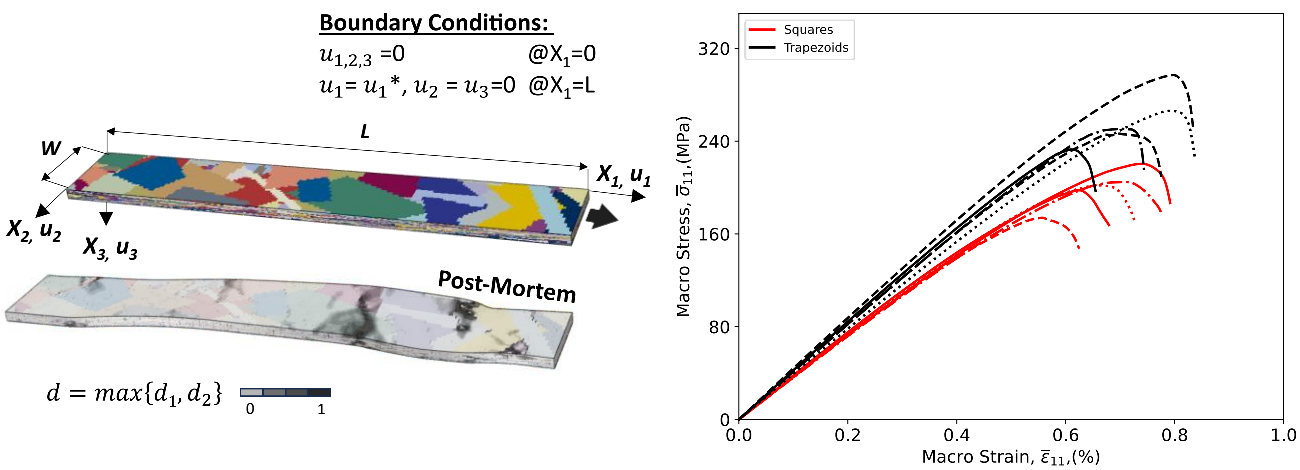

Figure 2. Stress-strain curves for coupons alongside a selected virtual TET coupon at the post-mortem stage of damage progression where the damage index is shown in greyscale.

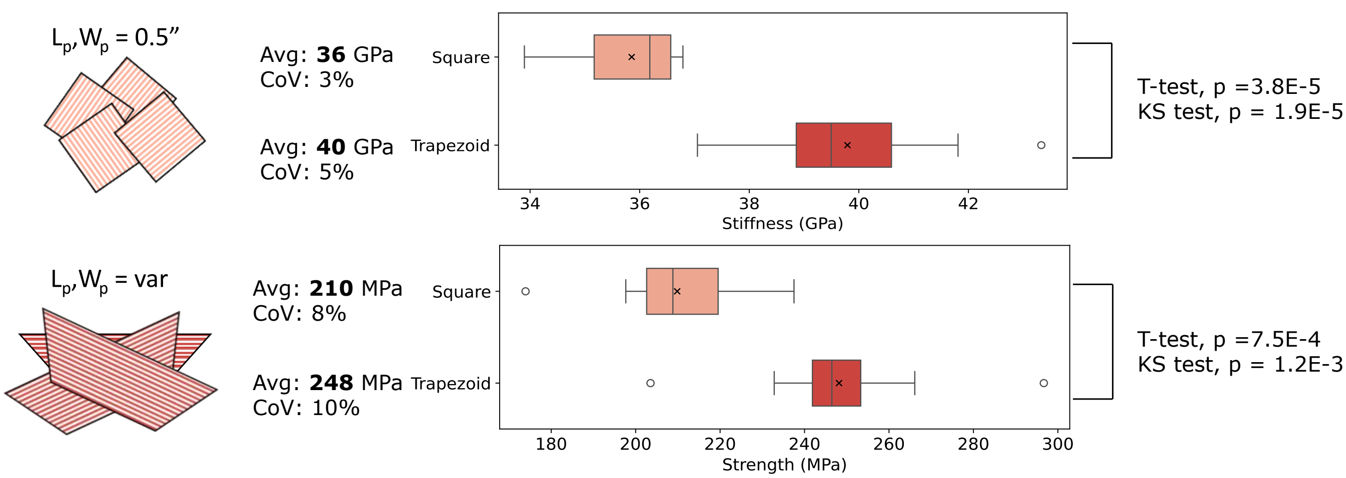

Figure 3. Tensile stiffness and strength of TET coupons made with constant or varying geometrical parameters.

Prior to damage initiation, the effective stress-strain response of a coupon is linear-elastic. With the incipience of the damage process zone, the load-carrying capacity of the composite is reduced and the coupon stress-strain relationship exhibits non-linear behavior as shown in Figure 2 [4]. Failure is observed to emanate from the free edges of the specimen with multiple cracks forming but with one major site of failure. Twisting-bending behavior (which occurs due to the non-symmetric distribution of geometric and material properties) similar to those described in other works was observed in both coupon types [4]. Results of the computational analysis demonstrate scatter in coupon stiffness and strength as shown in Figure 2, illustrating variable mechanical performance of this material. The strength and modulus vary due to the morphological dissimilarities between coupons.

To determine if there are statistically significant differences in the variability of tensile properties depending on the geometry of constituent platelets, comparison of the mean strength and stiffness were performed by two-sample Welch's t- tests and Kolmogorov-Smirnov tests. The null hypothesis claims that there is no difference between the two distributions. However, Figure 3 shows that the obtained p-values < 0.05 indicates that the null hypothesis can be rejected, deeming that the difference in the mean values of stiffness and strength of constant geometry (square) vs. variable (trapezoidal) platelets are statistically different at a 5% significance level.

5 CONCLUSION

A method for statistical quantification of the structure-property relationships in prepreg platelet molded composites comparing constant geometry vs trapezoidal platelets whose features are drawn from probabilistic distributions was presented. The presented method comprises of two components: a meso-structural generation algorithm and a finite element model. Generated meso-structures which reflect realistic platelet morphology distributions are imported to the finite element models. Initial progressive failure testing was conducted on 20 coupons (10 for each geometry) with the primary objective of demonstrating statistically significant higher stiffness and strength for coupons comprised of trapezoidal platelets with variable geometry. The proposed model will allow for the effect of processing parameters from the chopping process employed for TET to be explored prior to manufacturing, potentially allowing for cost and time saving.

6 REFERENCES

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