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Property modelling

Statistical modeling of effective elastic modulus for multiphased hybrid composites

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ABSTRACT

We explored the effective elastic moduli of hybrid composites by using different statistical models to understand and analyze the effect of fiber length distribution (FLD) on the mechanical properties. Micro-CT was used to investigate the internal structure of the hybrid composites, and FLD was calculated via image-processing for the composite samples. The interaction between inclusions and matrix was considered using a perturbed stress-strain theory. Statistical modeling with the Weibull, Log-normal and Generalized Extreme Value (GEV) functions was carried out to understand the role of skewness. The results show that different skewness and FLD have significant impacts on the effective elastic moduli of the hybrid composites, which demonstrates the practical importance of statistical modeling when evaluating and analyzing the their mechanical properties.

1. Introduction

Hybrid composites have been extensively studied to design superior materials that possess improved mechanical properties such as impact and tensile strength, fatigue resistance, toughness and interfacial adhesion between inclusions and matrix. The hybrid composites can lead to a synergetic effect often called a 'hybrid effect' [1–3]. For instance, the hybridization of short fibers and inorganic particles can have advantages on both tensile strength and modulus over using short fibers or inorganic particles alone in a polymer matrix due to a mixed inter/trans-granular fracture mode [4,5].

In general, composites are classified into isotropic, transversely isotropic and anisotropic systems according to their microscopic structure. The composite sphere model and the self-consistent scheme model describe the isotropic composite in which voids or rigid spheres are embedded in the matrix [6,7]. A composite system is referred to as transversely isotropic when cylindrical inclusions such as glass fibers are embedded in a matrix. Prior to analyzing the hybrid composite systems, the investigation of the microstructure becomes important to properly predict mechanical properties.

The influence of fiber length and orientation on mechanical properties becomes more obvious as inclusions in a matrix are long fiber-like shapes [8–12]. Recently, Micro-CT has been used to investigate the internal structure of composites. In particular, FLD can be obtained quantitatively by a CT scan. Once FLD is quantified, the effective elastic moduli of hybrid composites can be predicted using theoretical approaches such as the combination of laminating analogy approach (LAA) and statistical modeling. During composite manufacturing such as compounding, extrusion and injection molding, inclusions in the matrix can be severely broken, resulting in typically positive skewed FLD [2,11–14]. Since FLD is a deterministic factor in

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predicting the mechanical properties, a genetic algorithm for optimizing FLD has been proposed recently [15]. A multiphased hybrid composite model has also been proposed by using the meso-constitutive equation of a homogenized composite system through statistical averaging of fibers [16]. Typical statistical models with regard to fiber breakage are the Weibull and Log-normal models [11,17,18]. For instance, *Fu* et al. have adopted theoretical approaches to predict the effective elastic moduli of composites using the Weibull statistical function [10–12]. However, when fiber breakage gets severe, positive skewness can arise and the Weibull statistical function loses its reliability.

This present study proposes statistical modeling through adopting the Log-normal and GEV statistical functions as well as using the Weibull function in order to predict the effective elastic moduli for multiphased hybrid composites. During the analytical approach, perturbation theory and LAA were implemented to consider the effect of perturbed stress-strain for embedded inclusions and FLD. It is noteworthy that the statistical modeling gives good theoretical results that are comparable with the experimental ones, which underlines the importance of evaluating the statistical quantification prior to predicting the mechanical properties of hybrid composites. This theoretical achievement will help predict and understand the mechanical properties of multiphased hybrid composites.

2. Experimental

2.1. Specimen preparation and mechanical testing

Two types of liquid crystal polymer composites filled with different amounts of talc and glass fiber (Polyplastics, Vectra S471 and Vectra S475) were used for the experiments. Vectra S471 and Vectra S475 are denoted as S1 and S2, respectively. Tensile specimens were produced using an injection molding machine (Sumitomo, SE18D), and elastic moduli of the specimens were measured using a universal testing machine (UTM) (Instron, 8801) (SI Fig. 2). The crosshead speed was set at 5 mm/min according to ISO 527-1 for the tensile testing.

2.2. Micro-CT imaging and image processing

A high-resolution desktop X-ray Micro-CT system (Skyscan, 1172) was used to investigate the internal morphology of the hybrid composites. A 100 kV and 10 Mp X-ray source was employed for 2D image analysis. In order to acquire FLD from the Micro-CT data, image processing was performed by using a commercial image analysis tool (Media Cybernetics, Image-Pro Plus 7.0). The sectional images of specimens were manipulated by controlling the contrast and brightness and then transformed into binary images by using a thresholding method in order to discard bad pixels. The length of each fiber in a horizontal plane was calculated by collecting the chosen pixels.

2.3. Morphological characterization

The S1 and S2 samples were characterized morphologically by using a field emission scanning electron microscope (FE-SEM, Carl Zeiss, SUPRA 55VP) at 5.0 kV after incinerating the LCP pellets at 600 °C for 24 hours. The composition of talc and glass fiber in the hybrid composite was determined by an EDS method reported in our previous work [10].

3. Theories

3.1. Fiber length distribution (FLD)

Fiber breakage in composite systems can take place during polymer processing such as extrusion, mixing, and injection molding. The fiber length distribution induced by such fiber breakage results in attenuation of the mechanical properties of composites. Therefore, it should be noted that the quantification of FLD is indispensable to evaluate such mechanical properties of composites as stiffness, strength, toughness and fatigue resistance, which are essentially determined by a perturbed stress-strain relationship in the presence of inclusions.

The Weibull and Log-normal distribution functions are representative statistical models for describing FLD after injection molding of composites. In particular, the Weibull function can predict the breaking strength of material [10–12]. Its original form is as follows:

$$f(L) = (b/a)(L/a)^{b-1}\exp\left(-(L/a)^{b}\right) \tag{1}$$

where a and b are the scale and shape parameters, respectively. Another model for predicting FLD employs the logarithm distribution of the variable as below:

$$f(L) = \left(1\Big/\sigma\sqrt{2\pi}L\right)\exp\left(-(\ln(L)-\mu)^{2}\Big/2\sigma^{2}\right) \tag{2}$$

where μ and σ are associated with the mean and standard deviations, respectively. As fiber breakage becomes severe, an extreme value function can be more applicable since the probability density of broken fiber becomes significant. The GEV function is often used to model the smallest value among a large set of values as follows:

$$\begin{aligned} f(L) = {} & (1/\sigma)\exp\left(-(1+\kappa(L-\mu)/\sigma)^{-(1/\kappa)}\right) \\ & \times (1+\kappa(x-\mu)/\sigma)^{-(1+1/\kappa)} \end{aligned} \tag{3}$$

The parameters of σ, κ, and μ represent the scale, the shape and the location, respectively. The three statistical functions are validated with the proposed hybrid composite systems and used to formulate the overall laminate stiffness matrix.

3.2. Effective elastic modulus

The existence of inclusions in a matrix causes a perturbed strain due to the mismatch of stiffness between inclusions and matrix. For instance, a low perturbed strain is developed when embedding inclusions with low stiffness [19]. In this theoretical approach, talc with low stiffness was first considered to evaluate the effective elastic modulus, and then statistical functions acquired by the quantification of FLD from the experiment were combined with the stiffness matrix (Q_{ij}) transformed from the effective elastic moduli of composites (Fig. 1). The Tandon-Weng