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Finite element analysis and microscopy of natural fiber composites containing microcellular voids

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ABSTRACT

Mechanical behaviors of chopped, natural fiber composites with and without closed-cell microcellular foamed structures are investigated using finite element analysis (FEA), with references to previously conducted experimental measurements of the stress-strain characteristics of analogous test specimens and their microscopic images. Analytical and FEA models are compared for a simple, aligned fiber case; the FEA models are then extended to composites having more general fiber arrangements. These FEA results are compared to experimental stress-strain data. Scanning electron microscopy (SEM) images of fracture surfaces from test specimens are analyzed, and correlations between numerically predicted behaviors and fracture paths, and fracture surface images are discussed. The FEA results reflect experimental trends well including the effects of fibers and the presence of voids. These have also been found to induce specific regions of stress concentration. Inspection of fracture surfaces reveals transition from ductile to brittle behavior at low strain rates, generally brittle failure modes, and little evidence of fibers stressed to their tensile limits.

1. Introduction

Injection molded, chopped-fiber composites are of interest in manufacturing as an expedient and low-cost means of tailoring the properties of structural plastics. Glass fibers have traditionally been used as the reinforcing material in injection molded structures, but more recently, interest in supplanting glass with natural fibers has increased. Though natural fibers are generally less stiff than glass fibers, they offer advantages in cost, noise attenuation, recyclability, disposal, carbon footprint, and worker exposure hazard [1–6]. Because they are not a manufactured product, natural fibers possess a wide variety of variability including length, aspect ratio, surface condition, and elastic properties, making it important to establish methods for predicting behavior of polymeric composites made from them. Static macrostructural properties of chopped-fiber composites have been studied extensively [7–15]. Properties of natural fiber composites have received less study in this regard [1–3,5,16–22], and little research exists that investigates the microstructural behaviors of these composites [18,23–31]. This is particularly true for the fiber in the current study, wheat straw [32], that is typically thicker and shorter than more-commonly used natural fibers such as jute. Microstructural voids added by gas-foaming in the mold [18,23–25,27,28,33,34] offer a potential element of commercial value, but also add complexity in modeling.

In the present work, numerical FEA methods are used to explore the stress fields within the matrix and fibers, and along the fiber-to-matrix interface. Four lengths of fiber are separately considered in models having either solid or voided structure, the latter simulating a microcellular foam. Aligned-fiber FEA models are compared to analytical methods, then extended to non-aligned-fibers and microcellular structures. These models are configured to the geometric and elastic properties of wheat straw fiber and polypropylene (PP), and the predicted properties of the composites are compared to experimental data.

The findings show that fibers tend to produce stress concentrations at their tips, especially when they are aligned with the loading directions. Voids tend to result in stress concentrations on their material surface at points furthest from the axis of the loading direction. The interaction of these effects produces a structure that previous experiments by the present authors have shown to be stiffer and more brittle than pure PP, but with very little change in ultimate tensile strength [32]. The addition of microcells reduces overall stress levels at all strains by redistributing microstructural stress fields.

2. Finite element modeling

Models were built to investigate the properties of polypropylene plastic reinforced with short, arbitrarily-distributed fibers. Mechanical and geometric properties were chosen to simulate an inedible by-product of wheat straw fiber and Basell Pro-fax 6523 polypropylene homopolymer.

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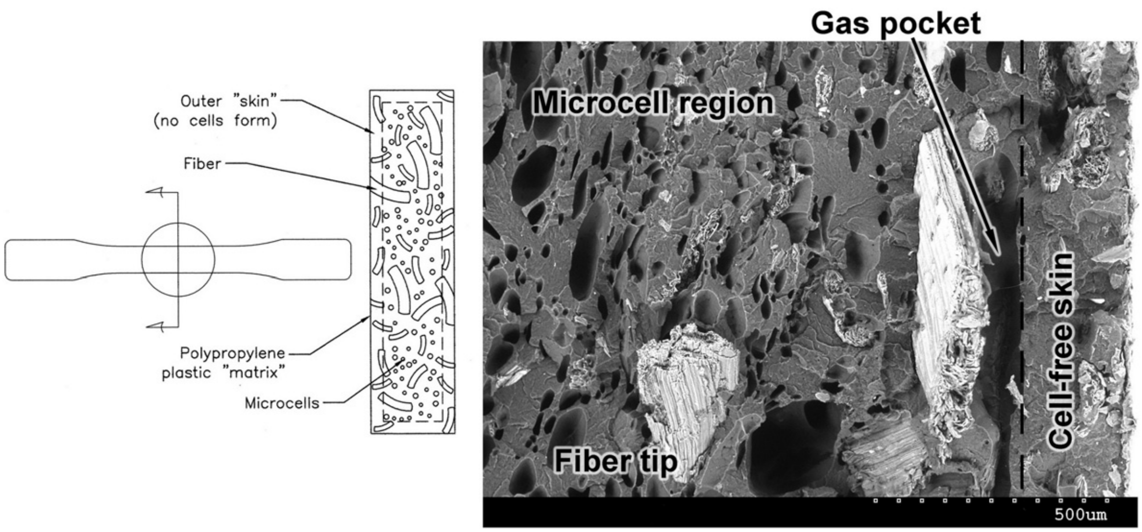

Fig. 1. Topography of a wheat straw specimen with microcellular structure. Fibers and cells in schematic at left are larger than true scale. At right is an SEM image of the fracture surface of a tested specimen (ASTM D638 Type I) showing a typical microstructure. The skin region tends to be free of voids. Void concentration increases away from the skin.

Table 1
Sizes and proportions of composite features.

Component	Actual size (μm)	Size normalized to cell diameter
Overall width	12,700	254.0
Overall thickness	3100	62.0
Skin thickness	450	9.0
Fiber diameter	100	2.0
Fiber length cases	1000	20.0
	667	13.3
	333	6.7
	167	3.3
Cell diameter	50	1.0

The structure of the modeled composite can be seen in Fig. 1. All specimens contain wheat straw fibers in the volumetric fraction of approximately 10% that are evenly distributed throughout the structure. The volumetric fraction of fibers was calculated from the known density values of PP and wheat straw fiber, and fiber mass fraction of 20% [2]. Here, foaming reduces the mass of the specimens by 10% in most cases, but cells tend not to form in a skin region along the outer surfaces, as is typical [35], and is probably due to dissolved gas diffusion into the core prior to bubble formation. Microcells are generally 25–50 μm in diameter. Process optimization is required to avoid formation of long, thin gas pockets which can form just inside the skin.

On the basis of available research [36–39] and SEM observations from the current study, the geometric parameters listed in Table 1 were used in the models. The fiber lengths of 167 and 333 μm were selected from the typical short fiber specimens, and the 667 and 1000 μm lengths were determined from the typical long fiber specimens, manufactured and tested in [32].

2.1. Construction of the finite element models

Except for a few special test cases, all FEA models represent the gauge section of ASTM D638 Type I test pieces. Models were constructed in AutoCAD 2013 as unit-thickness 3D solids, imported into Abaqus. All models, except as noted, were seeded with a global seed value of 20 μm, and meshed with elements of wedge type C3D6. In Figs. 12 and 13, this resulted in 26,398 elements in the fibers, 233,764 elements in the solid, and 228,374 elements in the microcellular matrices. The focus of this study is the in-plane response of the composites, such as in an axial loading test for characterization of the composites. As such, all loads are applied in-plane and the in-plane stresses are described. The matrix was configured in Abaqus using the second-order polynomial strain

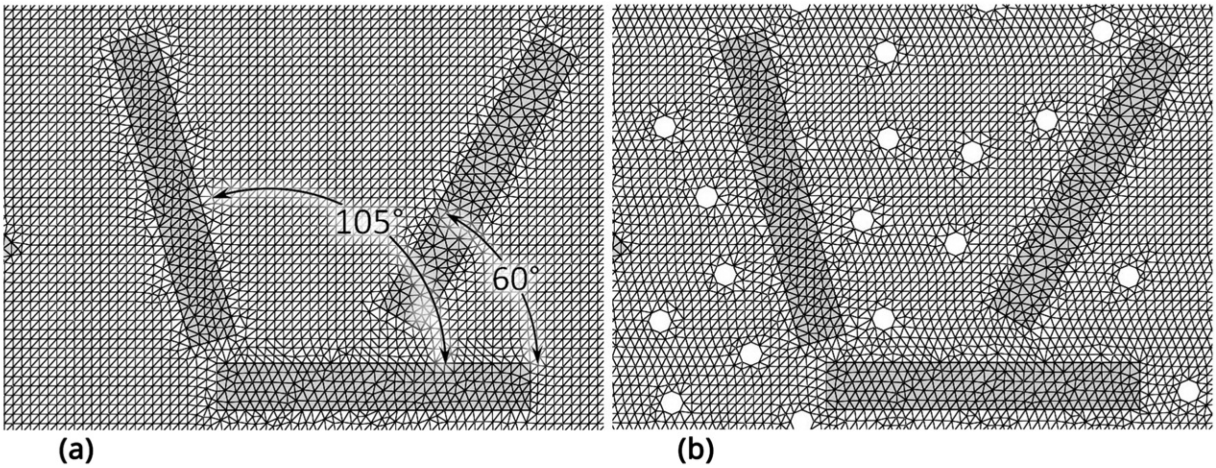

Fig. 2. Portion of FEA mesh of arbitrarily distributed wheat straw fibers embedded in (a) solid and (b) microcellular polypropylene matrix used for general models, with some discreet fiber angles shown.