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Fatigue of natural fiber thermoplastic composites

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ABSTRACT

The fatigue behavior of hemp-fiber–reinforced High Density Polyethylene (HDPE) composites is investigated using fatigue-life (*S–N*) curves at different fiber volume fractions. For this purpose, a new modified stress level is proposed to normalize the developed *S–N* curves into one normalized *S–N* curve. A generalized fatigue behavior model is developed to simulate the fatigue-life response of these composites. It is demonstrated that the developed model is capable of predicting the fatigue behavior of the natural fiber composites at different fiber fractions and fatigue stress ratios, and is also capable of accounting for the effect of moisture absorption.

1. Introduction

Composites are an important category of materials for engineering applications. They form an essential part in the design process in many sectors, including the automotive, marine and aircraft industries. Over the past decade, there has been an increased demand for "green" or natural-fiber–reinforced composites. Natural fibers provide many advantages over synthetic fibers, including low density (light weight), reasonable mechanical properties, and environmental benefits (including sustainability and a lower carbon footprint) [1–4]. However, the range of applications involving natural fiber composites in engineering design is still limited due, partly, to a lack of understanding of the long-term behavior of these materials especially under cyclic (fatigue) loading. Like all composites, this can be attributed to the complex nature of how these materials fail. Unlike monolithic materials (such as metals or polymers) where failure is associated with the initiation and propagation of a dominant fracture event, failure in composites is characterized by accumulation of multiple damage modes including [5–10]: (1) debonding between the reinforcing fibers and the polymer matrix; (2) fiber failure; and (3) matrix failure. These damage mechanisms take place independently or, more commonly, in a synergistic manner [11,12]. Natural fibers further complicate this behavior due to variation in properties and surface characteristics [13,14].

Furthermore, natural fibers have a tendency to absorb moisture from air or direct contact with water or other liquids due to their hydrophilic nature. Natural fibers are mainly composed of three constituents: cellulose, hemicellulose and lignin [14]. Cellulose, a semi-crystalline polysaccharide, is the main constituent of most natural fibers, and is also the component responsible for its excellent structural properties. Cellulose is also hydrophilic, and is the main cause of water uptake in natural fibers. Hemicellulose is an amorphous polysaccharide, and is partially soluble in water. Finally, lignin is a complex polymer which acts as a binder for the other components (cellulose, hemicellulose and others) in natural fibers. Lignin is mainly hydrophobic in nature. Studies on natural fiber composites have shown that absorbed moisture weakens fibers and the bonding between the fiber–matrix interface, resulting in an overall reduction in mechanical properties [15–17].

The fatigue behavior of fiber reinforced composites has been studied extensively over the past four decades [5,9,10,18,19]. A majority of these studies, however, are related to long-fiber composites made with glass, carbon and aramid fibers. A smaller subset of studies has focused on the cyclic performance of short fiber reinforced composites made from synthetic fibers such as glass and carbon. Mandell et al. [20] conducted a comprehensive investigation of the fatigue response of a variety of reinforced thermoplastics with both chopped glass and carbon fibers. The authors showed that the fatigue behavior of the composite was a function of the matrix properties (in particular, ductility), fiber type, and the quality of the fiber/matrix interface. The response of carbon fiber composites tended to be matrix and interface dominated, while glass fiber composites exhibited more fiber dominated behaviors.

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Lavengood and Gulbransen [21] studied the cyclic response of short fiber boron/epoxy composites and found that fatigue life increased with increasing fiber aspect ratio (to a maximum). Harris et al. [22] compared the fatigue life behavior of long versus short random fiber composites with the same carbon/epoxy constituents. It was found that the long fiber composites had better overall fatigue life properties than their short fiber counterparts, but the fatigue sensitivity was greater (steeper decline over the fatigue-life curve).

For natural fiber based composites, there has been a great deal of work focused on determining static mechanical properties [23–28], but very limited studies related to fatigue. Towo and Ansell [29] investigated the cyclic behavior of sisal fiber reinforced thermoset composites under both tension–tension fatigue and fully reversed loading. This study found that alkali treated fiber composites had better fatigue performance due to improved fiber–matrix adhesion. Yang et al. [30] studied the flexural fatigue behavior of wood flour reinforced high density polyethylene. In their study, a statistical model using a Weibull distribution was developed to predict the fatigue behavior of these materials. Belaadi et al. [31] studied the fatigue behavior of unreinforced sisal natural fibers, and found that conventional empirical fatigue-life models worked well to correlate fatigue response.

In this current study, experiments were performed on natural-fiber–reinforced thermoplastic composites under cyclic loading, and a new semi-analytical model was developed which predicts the fatigue behavior of these materials. This model predicts the fatigue life of these materials as a function of loading condition, fiber fraction, and moisture absorption. Fatigue stress-life (S–N) curves were used as a tool to study and to model the fatigue behavior of natural fiber composites.

2. Experimental behavior of hemp–reinforced composites under monotonic and cyclic loading

2.1. Materials and methodology

In this study, a series of monotonic and cyclic tests were performed on test specimens made from natural-fiber–reinforced thermoplastic composites. High Density Polyethylene (HDPE) was used as the polymer matrix, and chopped hemp bast fibers (<5 mm length) were used as the reinforcement. The HDPE polymer (HD360) was supplied by M. Holland Company, and the hemp fibers were grown and processed at Alberta Innovates–Technology Futures' (AITF) research facilities in Alberta, Canada. The bast fibers were extracted from hemp stalks using a custom built, short fiber decortication system. Chopped bast fibers used in this study were not modified or chemically treated. Table 1 shows the mechanical and physical properties of the HDPE. The hemp fibers and HDPE were mixed at two fiber fractions (weight percentages of 20% and 40%) using a PTW 24/40 Thermo-Fisher-Scientific twin-screw extruder/compounder. The density of the hemp bast fiber was 1.475 g/cm^3 as measured using the Archimedes' method, modified for natural fiber applications [32]. This measured density was found to be very close to values reported in the literature [33]. Based on the hemp fiber density, the estimated volume fiber fractions (υ_f) were calculated to be 13.5% and 30.1% for the 20% and 40% weight fractions, respectively. Test specimens, for both monotonic and fatigue tests, were manufactured using a Battenfield 100 injection molding machine according to ASTM D 638-03 (Type I test specimen with 3 mm thickness and 50 mm gage length – see Fig. 1). All mechanical tests (monotonic and cyclic) were performed using an Instron 8501 universal testing machine under controlled ambient conditions (23 °C and 50% relative humidity environment). Elongation (up to 50%) was measured using an extensometer (50 mm gage length) attached to the test specimen.

To investigate the effect of moisture absorption, 20% hemp–HDPE and unreinforced HDPE specimens were immersed in water for 35 days, prior to mechanical testing. After 35 days, the 20% hemp–HDPE specimens absorbed approximately 2.4% of its original weight, while the unreinforced HDPE specimen did not absorb any measurable amount of moisture. This demonstrates that moisture uptake in these composites is entirely due to the presence of the natural fibers.

Fatigue tests were conducted under tensile–tensile cyclic loading at two different fatigue–stress ratios (R = min. fatigue load/max. fatigue load) of 0.1 and 0.8. All fatigue tests were conducted under load (stress) control at a maximum frequency (f) of 3 Hz (tests conducted at frequencies above 3 Hz had significant self-heating or autogenous temperature effects. The fatigue stress levels used in the cyclic tests were chosen based on percentages of the monotonic strength, and are follows: 80%, 70%, 65%, 60%, 55% and 40% for unreinforced HDPE; and 85%, 80%, 75%, 70%, 65%, 60%, 55%, 50% and 40% for 20% hemp–HDPE; and 80%, 75%, 70%, 65%, 60%, 55%, and 40% for 40% hemp–HDPE; and 80%, 70%, 65%, 55%, 45% for 20% hemp–HDPE with moisture. Fatigue tests were repeated three times at each stress.

In addition to the cyclic tests, a series of monotonic tensile tests were also performed at a various strain rates to simulate the loading ramps under fatigue conditions. The resulting monotonic data was used to develop the fatigue model in subsequent sections. Initial attempts were made to conduct the monotonic tests under stress control, but control problems were encountered at the high rates of loading. As such, monotonic tests were subsequently performed under strain controlled conditions to ensure repeatable and controllable responses. Based on the stress and strain at failure from these strain based tests, an effective (approximate) stress rate was calculated for each strain rate condition. Using this method, the monotonic results from strain controlled tests were used to approximately correlate the fatigue loading ramps under stress control (see Sections 3.1 and 3.3). Strain controlled tests were conducted at engineering strain rates ($\dot{\varepsilon}$) of 0.13, 0.50, 1.00, 2.00, 6.00, 8.00, 10.00 and 14.00 min^{-1}, which correspond to elongation speeds of 6.5, 25, 50, 100, 300, 400, 500 and 700 mm/min, respectively. Similar to the cyclic tests, all monotonic tests were repeated at least three times with the final results being averaged.

For monotonic and fatigue tests, the failure criterion was defined based on the observed failure modes. For unreinforced HDPE, the failure mode was found to be ductile failure (with necking). As such, the point of necking was selected as the failure criterion for monotonic tensile tests. The maximum engineering tensile stress

Table 1
Mechanical and physical properties of HDPE.

Property	HDPE	Test method
Density	0.943 ± 0.02 g/cm^3 (3 tested samples)	ASTM D1505
Tensile strength at yield (50 mm/min)	24 ± 0.26 MPa (3 tested samples)	ASTM D638
Stiffness (Young's modulus) (50 mm/min)	1.8 ± 0.143 GPa (3 tested samples)	ASTM D638
Elongation at yield (50 mm/min)	9% ± 0.43% (3 tested samples)	ASTM D638
Melt mass flow rate (from manufacturer table) (190 °C/2.16 kg)	7.5 g/10 min	ASTM D1238