Composites: Part B 69 (2015) 435–442

Contents lists available at ScienceDirect

Composites: Part B

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

An analytical model for predicting the freeze–thaw durability of wood–fiber composites

Wil V. Srubar III

Department of Civil, Environmental, and Architectural Engineering, Sustainable Infrastructure Materials Laboratory, University of Colorado Boulder, ECOT 441 UCB 428 Boulder, CO 80309, USA

ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form 4 October 2014
Accepted 7 October 2014
Available online 22 October 2014

Keywords:
A. Natural-fiber composites
A. Polymer–matrix composites (PMCs)
B. Environmental degradation
C. Micro-mechanics

ABSTRACT

The development and validation of an analytical model that predicts the onset of frost-induced damage in wood–plastic composites (WPCs) is presented in this work. The mathematical model is based on the mechanics of a hollow cylinder subjected to an internal pressure caused by the expansion of freezing moisture bound in the wood–fiber reinforcement. The model is substantiated using experimental data from several published studies. Using a stochastic approach, the model is implemented to analyze the effect of wood fiber specie, fiber volume fraction, and matrix material properties on the frost resistance of fully and partially saturated WPCs. Results show that WPCs with high fiber contents, high moisture contents, and low polymer tensile strengths are most susceptible to frost-induced damage. Data also suggest that the use of softwood fibers (e.g., pine, spruce) and polymers with low moduli and high tensile strengths enhances the frost-resistance of WPCs.

1. Introduction

Interest in the use of lignocellulose-based wood–plastic composite (WPC) materials in the packaging, automotive, and construction industries has increased in recent years due to the environmental, mechanical, and economical advantages of natural fibers [1]. While significant technological and scientific advancements have improved the processing and mechanical properties of WPCs, persistent concerns regarding the durability of natural-fiber composites have inhibited confidence in their long-term performance, limiting their widespread application.

Previous research has shown that WPCs are highly susceptible to environmental aggressors [2]. For example, in high humidity and wet environments, natural fibers in WPCs absorb moisture, which can cause material property degradation [3] and dimensional instability [4] and can increase susceptibility to biological fungal attack [5]. Under constant mechanical loads, high temperatures exacerbate creep deformation [6], while low temperatures, in combination with absorbed moisture, promote frost-induced deterioration. Outdoor exposure can also lead to discoloration and embrittlement, which is attributable to UV-induced photo-oxidation [7].

The majority of research concerning the durability of WPCs has been experimental, centering on the characterization of moisture-induced reductions in mechanical properties [3,8–10], thickness swelling [4,11], rates of water transport [12–14], and the fungal resistance [5,11] of synthetic polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) matrix composites. Poor freeze–thaw resistance of WPCs has also been noted as a primary durability concern [15–20]. Wood fiber reinforcement is well known to expand upon the absorption of moisture. Absorbed moisture will further expand upon freezing, causing the development of internal stresses that promote cracking in the surrounding polymer matrix.

Experimental studies have confirmed that moisture- and frost-induced dimensional changes cause mechanical property degradation in WPCs. For example, Pilarski and Matuana [15] found that the flexural stiffness and strength of fully saturated maple and pine wood flour-reinforced high-density PE (HDPE) matrix WPCs decreased 49% and 21% and 37% and 5% after 15 freeze–thaw cycles, respectively. This effect is exacerbated in WPCs with high wood–flour contents [15,16]. In a similar study of beech wood flour–reinforced PVC matrix WPCs, Tajvidi and Haghdan [17] reported that the majority of frost damage occurred after only one freeze–thaw cycle. Some authors have attributed the loss in mechanical properties to initial moisture absorption rather than freeze–thaw cycling [15,16]. However, other studies have shown that moisture absorption alone does not necessarily reduce the performance of WPCs [18,21].

While WPC empirical data is widely available, the development and implementation of durability-based service-life models for

---

E-mail address: wsrubar@colorado.edu

http://dx.doi.org/10.1016/j.compositesb.2014.10.015

WPCs remains limited. Modeling efforts have focused on rule-of-mixture [22,23], viscoelasticity [24,25], and diffusion-based transport [14,26] models. A model for predicting liquid moisture-induced damage was recently developed by the author [10]. To date, however, no analytical or numerical models have been developed to capture the deleterious effects of freezing internally bound moisture in natural-fiber composites.

This study presents the development and implementation of a mathematical model that predicts the onset of frost damage in WPCs. The model is based on pressure-vessel mechanics in which a hollow cylinder is subjected to an internal pressure caused by the freezing and expansion of absorbed bound water in the wood fiber reinforcement. The model, which is validated herein using experimental results from literature, is subsequently used to analyze the effects of wood specie, initial degree of saturation, and matrix properties on the freeze–thaw resistance of WPCs.

2. Model development: assumptions and theoretical formulation

The proposed WPC frost-induced deterioration model is an extension of a previously developed moisture-induced micromechanical damage model [10] based on the generalized self-consistent scheme for fiber-reinforced composites first proposed by Hill [27]. In Hill's micromechanical model, individual, discontinuous fibers are idealized as cylindrical inclusions enclosed by a concentric, polymer matrix shell. While Hill's model has been used to predict initial mechanical properties of fiber-reinforced polymers, researchers recently validated a damage model that combined Hill's self-consistent scheme with Lamé's mechanics equations for cylindrical pressure vessels to predict the onset of corrosion-induced cracking in reinforced concrete structures [28].

The frost damage mechanism in WPCs is analogous to corrosion-induced cracking and deterioration of steel-reinforced concrete structures. Absorbed moisture causes wood fibers to swell, inducing an internal pressure to the surrounding polymer matrix in much the same way the expansion of corrosion products induce an internal pressure to concrete. While moisture causes initial fiber expansion that can lead to matrix cracking [10], the freezing of internally absorbed moisture causes additional expansion, which may exacerbate damage. The proposed model is formulated to predict critical volume fractions at which freezing causes damage in WPCs.

2.1. Modeling assumptions

The following assumptions were made in the formulation of the deterioration model:

1. Wood fibers are homogeneous, axisymmetric, identical in size and shape (cylindrical), uniformly dispersed, and longitudinally aligned.
2. Wood fibers, which have an initially microporous structure, have been compressed by the high-pressure injection and/or extrusion processes, thereby removing any internal voids created by hollow lumen structures [29,30]. The resulting individual particle reinforcement is comprised only of wood cell wall material.
3. Fiber swelling and damage is due to moisture absorption and freezing of the absorbed moisture in an individual fiber. Moisture absorption processes in wood have been widely studied and are well understood. Wood cell walls absorb moisture up to their fiber saturation point (FSP), which is well characterized to be 28–32% by weight of wood. While mildly temperature-dependent, the wood cell wall FSP is independent of wood specie [31]. Fibers are considered fully saturated when the cell walls of the filler reach the wood cell wall FSP.
4. The polymer matrix is assumed hydrophobic and homogenous, exhibiting isotropic, linear-elastic mechanical behavior.
5. A concentric polymer shell surrounds each individual fiber and is treated as a thick-walled cylinder subjected to an internal pressure, p_i, and an external pressure, p_e. The thickness, t_{eff}, of an effective cylindrical shell provides restraint against fiber expansion. The thickness is dependent upon the (a) volume fraction and (b) geometrical packing arrangement (e.g., square, hexagonal) of the wood fibers.
6. External pressure, or expansion, from neighboring fibers and shells is neglected. The model is formulated to predict the formation of cracks along the outer composite surface.
7. Effects due to the rate of freezing and freeze–thaw cycling are also neglected. Research studies show that initial freezing of saturated composites cause the majority of losses in structural integrity [18,21].
8. The stresses in the cylindrical shell are induced only by internal pressures generated by fiber expansion upon moisture absorption from an oven-dry state to the FSP (from 0% to 30% by weight of filler) and subsequent freezing of the absorbed moisture from a liquid to a solid state. Effects due to mechanical coupling are not considered.

2.2. Theoretical formulation

The model problem is depicted in Fig. 1. As discussed, the effective thickness is dependent upon the volume fraction and packing arrangement of fibers. Both square and hexagonal packing arrangements were considered. The internal pressure induced by freezing internally absorbed water was calculated using mechanics principles of statically indeterminate structures [32] in which fibers

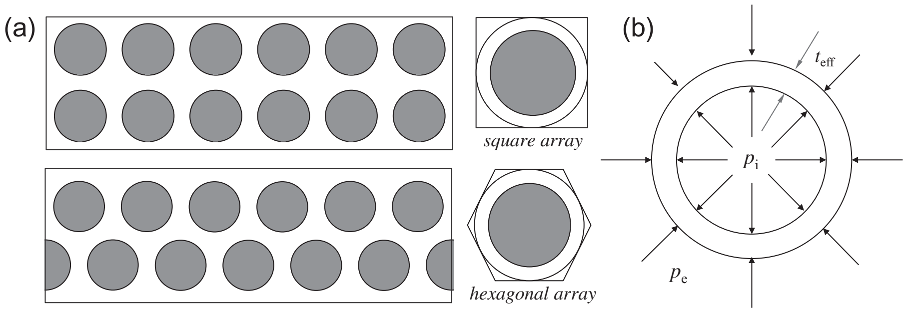

Fig. 1. Illustration of the model problem. This study considers (a) both a square and hexagonal packing array of wood fibers that are each (b) encapsulated by an idealized polymer shell with effective thicknesses dependent upon fiber volume fraction and packing arrangement.