Composites Science and Technology 95 (2014) 67–74

Contents lists available at ScienceDirect

Composites Science and Technology

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

Mechanics of composite sandwich structures with bioinspired core

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ARTICLE INFO

Article history:
Received 27 July 2013
Received in revised form 7 February 2014
Accepted 11 February 2014
Available online 17 February 2014

Keywords:
A. Sandwich
B. Mechanical properties
B. Plastic deformation
C. Elastic properties
C. Damage mechanics
C. Deformation
Composite

ABSTRACT

Synthetic sandwich composite materials have been fabricated using carbon fiber–epoxy face sheet and polymeric foam core by mimicking the structure of a natural composite material, Palmetto wood. The foam core of the sandwich composites has been reinforced by pultruded carbon rods to replicate macrofiber reinforcement of Palmetto wood within the porous microstructure for enhanced flexural behavior and energy absorbance. Sandwich structures have been characterized to elucidate the multiscale deformation behavior under quasi-static three point bend test using multiscale Digital Image Correlation (DIC). The damage evolution in the sandwich materials has been evaluated using a model developed to decouple the effect of pore collapse and plastic strain. It has been observed that the longitudinal reinforcement of pultruded carbon rod in foam core by the bioinspiration from the hierarchical structure of Palmetto wood increases the flexural strength, elastic energy absorbance of the sandwich with bioinspired core compared to that with the conventional un-reinforced core, however, at the cost of damage initiation strain. The sandwich composites with bioinspired core exhibits an increase of approximately 100% in flexural stiffness compared to that of sandwich with conventional foam core. The strength and volumetric energy absorbed are found to increase by approximately 10× and 14× from the sandwich with conventional core. These results validated using Palmetto wood as a source of bioinspiration for increasing the energy absorbing capability of sandwich composites. The analysis of the experimental results also indicated that the macroscopic flexural response of the sandwich composites is similar to that of the Palmetto wood. This similarity is attributed to the evolution of damage mechanisms associated with pore collapse and plastic strain being nearly identical between the bioinspired core and Palmetto wood. Furthermore, it is found that the reinforcement does not significantly affect the damage evolution characteristics in the bioinspired core, only the damage initiation is affected similar to what was observed in Palmetto wood.

1. Introduction

Significant efforts have been employed to develop synthetic material systems that exhibit enhanced properties and functionalities. Recently, nature has been a source of inspiration to engineer better materials and designs with its optimally designed biological systems. By virtue of unique structural features at the nano-, meso- and microscale (i.e., multi-scale structure) that hierarchically organize organic and inorganic constituents into structural elements possessing unique properties and functionality across those length scales, natural materials are unique composites that can exhibit remarkable combinations of physical properties and functionalities at the macroscale [1–3]. Researchers have developed several bioinspired and biomimetic materials and devices that are aimed to function like their natural inspiration. Several studies have been performed to investigate the structure–property relationships in natural composite materials to understand their mechanical behavior to develop synthetic bioinspired composites, such as *Terrapene carolina* carapace [1], crustacean exoskeleton [4], several shells like *Strombus gigas* (conch) [5], *Haliotis rufescens* (abalone) [6], and nacre [7]. The bioinspiration from the nature has been utilized in design of several composite materials like platelet reinforced polymer film [8], and particle polymer composite [9].

The successful use of Palmetto wood as an energy absorbing material was first observed during the Revolutionary and Civil war when it was used as fortification of Fort Moultrie in Charleston, South Carolina, which motivated investigating it further as a source of bioinspiration [10,11]. Multiscale characterization of Palmetto wood has revealed both its hierarchical structure and how the structure contributes to enhancing mechanical behavior [12,13]. The unique aspect of Palmetto wood has been found to be the hierarchical structure resulting from the reinforcement of a porous cellulose microstructure with macrofibers. Thus, a fundamental transformation in the general engineering of porous

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http://dx.doi.org/10.1016/j.compscitech.2014.02.011
0266-3538/

materials can be established through the biologically inspired concept of reinforcing foams with macrofibers in order to develop sandwich composite structures with enhanced mechanical behavior. To characterize the mechanical behavior of Palmetto wood at multiple length scales, the full-field deformation measurement technique known as Digital Image Correlation (DIC) was used on deformed images obtained at several magnifications [13]. Pore collapse and shear-dominated debonding of the porous matrix–macrofiber interface were found to be the key failure mechanisms in Palmetto wood [13]. In order to quantify the evolution of damage in Palmetto wood, a uniaxial damage model was developed to relate the global plastic strain and damage [14].

Sandwich composite structures are advanced structural composites that have been design favorite for high stiffness-to-weight ratios for several applications [15]. These materials consist of a core material, generally light and soft to enhance energy absorption, damage resistance and transverse shear sandwiched between two face sheets with considerably greater strength, stiffness, and density than the core to provide stiffness, tensile as well as bending. Extensive research has been performed on the investigation of foam core sandwich composites to study their mechanical behavior [16], impact response [17,18], failure mechanisms [19] and damage [20], fracture behavior [21] and buckling [22]. Earlier, reinforcement in sandwich composite structures has been employed in the thickness direction to develop Z-pinned sandwich composites [23,24]. The through-thickness reinforcement has been found to significantly enhance the compressive, shear strengths of the sandwich composite [23–27].

Inspired by the structure of Palmetto wood (Fig. 1(a)), we have developed a bioinspired core for sandwich composite structures (Fig. 1(b)) consisting of pultruded carbon fiber rods within polymer foam. However the reinforcement in these structures is fundamentally different from the Z-pinned sandwich composites, where the reinforcements are in thickness direction as opposed to longitudinal direction in the present case. The mechanics associated with the additional interfaces in the core of sandwich composite structure due to the presence of macrofibers was then investigated to determine the potential for increasing the energy absorbance and damage resistance through the accumulation of high shear strains within the three-dimensional core instead of just at the two-dimensional core-face sheet interface. To elucidate on the mechanisms controlling the mechanical behavior, the deformations of the bioinspired core were investigated at multiple length scales using DIC. New uniaxial constitutive models for the macroscopic behavior of the bioinspired core could then be developed based on the associated mechanisms.

2. Materials and experiment

2.1. Specimen preparation

The materials used to prepare the composite sandwich specimens with bioinspired core are polymeric soft foam (density 35 kg/m^3), epoxy carbon fiber laminates and pultruded carbon rods (density 1600 kg/m^3) from The Composites Store and epoxy resin 105 and slow hardener 206 from West System. The bioinspired core of sandwich specimens was reinforced by carbon rods to mimic the hierarchical structure of Palmetto wood. The face sheets of carbon epoxy laminates (The Composite Store) of 0.05 inch thickness were adhered to the core using the epoxy based adhesive prepared from resin 105 and hardener 206 mixed by 5:1 ratio by weight. The reinforcement of carbon rods have been used by penetrating the carbon rods in the soft foam core after dipping them in the adhesive to achieve better adhesion with the foam. The glued and reinforced specimens were cured in a closed chamber at 80 °C for 30 h under a weight. The sandwich core thickness was

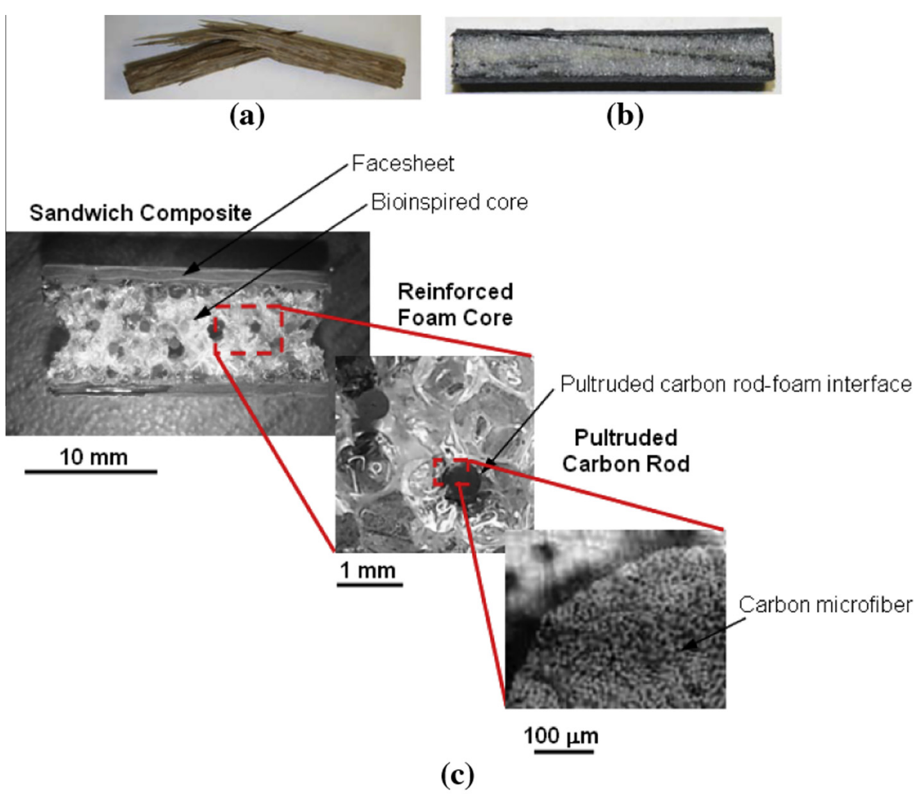

Fig. 1. (a) Palmetto wood, (b) sandwich composite with bioinspired polymeric foam core and carbon fiber–epoxy face sheets and (c) hierarchical structure of the bioinspired sandwich composites.