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Dynamic compressive behavior of woven flax-epoxy-laminated composites

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A R T I C L E I N F O

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A B S T R A C T

Currently, natural fiber-reinforced composites serving as building blocks for structural parts have attracted increasing attention in the automotive industry due to demands of energy and environmental sustainability. In this study, woven flax–epoxy-laminated composites were fabricated using vacuum-assisted resin infusion. The in-plane and out-of-plane compressive behavior of the fabricated specimens was experimentally studied from quasi-static to dynamic loading. Dynamic experiments revealed remarkable strain rate sensitivity for both loading directions. The ultimate stress and specific energy absorption for in-plane loading increased by 49.6% and 30.4%, respectively, as the strain rate varied from 3.0×10^{-3}/s to 2.8×10^{3}/s, while increased by 61.2% and 25.9% for out-of-plane loading cases. Final deformation photographs, high-speed camera images, and scanning electron micrographs of the flax fiber composites clearly illustrated their damage evolution and various failure mechanisms, including fiber buckling, matrix crack, fiber pull out, and fiber fracture at different strain rates and loading directions. Finally, a detailed computational model considering damage evolution and strain rate is established and verified by experiments for in-depth investigation. These results may serve as a guide for the future application of natural fiber-reinforced composites in the automotive industry.

1. Introduction

Composite materials with ultra-high specific stiffness and strength have attracted increasing attention in the automotive industry due to their lightweight characteristic [1,2]. In particular, natural fiber-reinforced composites with good recyclability and low cost have gained broad interest due to demands of energy and environmental sustainability [3–5]. The mechanical behavior of natural fiber-reinforced composites as potential substitutes to synthetic fiber (carbon and glass fibers)-reinforced composites has been investigated [6–10]. Flax fiber-reinforced composites as excellent candidates have become a hot topic over the past decades because of their competitive mechanical properties, such as high specific strength and stiffness [11–15].

Previous experimental and numerical investigations focused on the typical mechanical behavior, including tensile and compressive properties, fatigue, and damage, of flax fiber-reinforced composites. For example, Charlet et al. [11] found that the tensile properties of flax–epoxy composites could be strengthened by increasing the fiber volume fraction. Bos et al. [16] studied the compressive characteristic of unidirectional flax–epoxy composites and found that fiber kinking causes strength deterioration. Bensadoun et al. [17] showed that the high static modulus and strength of flax fibers benefit the fatigue characteristics of flax–epoxy composites and that their fatigue behavior is extremely dependent on the fiber architecture. Damage evaluation of flax–epoxy composites is also crucial for their engineering applications. Liang et al. [18] utilized transverse crack density as a basis for damage assessment by observation of the fractured edges and the internal crack under scanning electron microscope and optical microscope, respectively. Mahboob et al. [19] studied damage evolution by measuring evolving stiffness and permanent deformation, and SEM observations indicated that damage first appears at the fiber–matrix interface or within the fibers. Torres et al. [20] and Blanchard et al. [21] have recently proposed a statistical analysis and a multi-scale method to investigate the mechanical behavior of fiber composites, respectively.

Composites experience dynamic loadings during their services as a structural/semi-structural part [22–24]. The dynamic properties of composites, particularly carbon [25–27] or glass [28–30] fiber-reinforced composites, have been investigated experimentally and computationally. Hosur et al. [31] tested the dynamic responses of carbon/epoxy unidirectional and cross-ply laminates. They found that the dynamic stiffness and strength of these laminates are larger than their counterparts in quasi-static condition. Khan et al. [32] found that the

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Nomenclature

A_b	cross sectional areas of striker, incident, and transmitted bars (unit: mm^2)
A_s	cross sectional area of specimen (unit: mm^2)
c_0	wave speed in striker, incident, and transmitted bars (unit: m/s)
E_b	young's modulus of striker, incident, and transmitted bars (unit: GPa)
$F_i(t)$	force at the incident bar-specimen interface (unit: kN)
$F_t(t)$	force at the transmitted bar-specimen interface (unit: kN)
$V_i(t)$	particle velocity at the incident bar-specimen interface (unit: m/s)
$V_t(t)$	particle velocity at the transmitted bar-specimen interface (unit: m/s)
$\varepsilon_i(t)$	incident strain pulse
$\varepsilon_r(t)$	reflected strain pulse
$\varepsilon_t(t)$	transmitted strain pulse
$\dot{\varepsilon}(t)$	strain rate of specimen
$\varepsilon(t)$	strain of specimen
$\sigma(t)$	stress of specimen (unit: MPa)

woven S2-glass-reinforced polyester is highly sensitive to strain rate. Similarly, Arbaoui et al. [33] confirmed that woven E-glass/vinylester-laminated composites have strong material sensitivity to dynamic loading.

However, the limited information on the dynamic mechanical behavior of flax fiber-reinforced materials limits the application of such environment-friendly materials as building blocks of structural/semi-structural parts. To bridge this gap, the present study investigated experimentally the effect of strain rate on the in-plane and out-of-plane compressive behavior of woven flax–epoxy-laminated composites by targeting the specimens fabricated by vacuum assisted resin infusion (VARI) with woven flax and epoxy resin. In particular, high-speed photographs were recorded during the dynamic testing to visualize the deformation and damage evolution of the composite material and reveal the fundamental damage mechanism. Finally, a detailed computational model of flax fiber laminated composites is established and verified by experiments.

2. Experimental

2.1. Fabrication of material and specimen

The woven laminated composites selected in this study were based on epoxy resin matrix (LY 1564/Aradur 22,962, Huntsman) reinforced with flax fiber-weave with a surface density value of 20 mg/cm^2. Fabric morphology was observed using an optical microscope, as shown in Fig. 1(a).

Laminates were produced by VARI, as illustrated in Fig. 1(b). In the beginning, 20 layers of dry flax fiber weave were stacked on an aluminum sheet mold painting with mold-releasing agent. Then, the released cloth and resin infusion net were employed, and two spiral pipes were allocated for vacuuming and resin injection. Finally, the entire assembly was sealed in a vacuum bag with adhesive sealant. After complete saturation with epoxy resin, the entire assembly was placed in an oven at 80 °C for up to 2 h and then at 120 °C for 3 h for curing. A rectangular laminate about 10 mm thick was obtained [Fig. 1(c)] and then cut into cubic specimens of 10 mm × 10 mm × 10 mm for mechanical characterization [Fig. 1(d)–(e)]. Subsequently, the cutting surfaces of these specimens were polished to ensure parallelism and flatness.

2.2. Mechanical experiments: from quasi-static loading to dynamic loading

Two types of compressive loading, namely, quasi-static and dynamic loading, including two loading directions, namely, in-plane (parallel to the weave plane) and out-of-plane (normal to the weave plane), were adopted (Fig. 2). Quasi-static tests were conducted based on INSTRON-8801 with a constant loading speed of 2 mm/min (i.e., nominal strain rate of 3.0×10^{-3}/s) at room temperature, as illustrated in Fig. 3. Two repeated tests for each loading direction were conducted to ensure the repeatability of experiments. The compression force and displacement were measured using INSTRON-8801 sensors.

Dynamic loading experiments were conducted in a Split-Hopkinson pressure bar (SHPB) testing system, as shown in Fig. 4. In this test, the elastic modulus and density of these bars were $E = 200$GPa and $\rho = 8100$kg/m^3, respectively. The striker, incident bar, and transmitted bar were 300, 1200, and 1200 mm long, respectively, and 19 mm in diameter.

The specimen was sandwiched between the incident and transmitted bars. An elastic compressive wave formed when the striker bar launched from the gas gun impinged the incident bar, and then it propagated through the incident bar toward the specimen. Once the stress wave arrived at the interface between the incident bar and the specimen, a portion of the wave was reflected into the incident bar, and

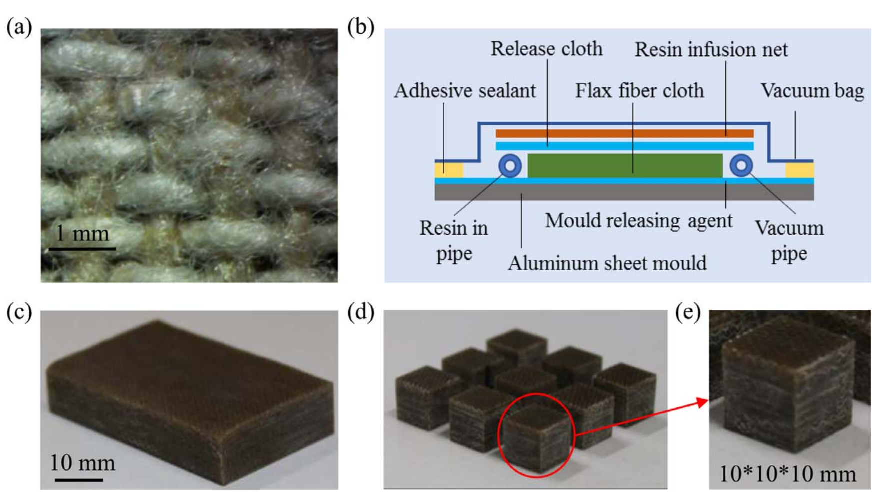

Fig. 1. Fabrication of laminated composites reinforced with (a) flax fiber weave based on (b) VARI. (c) Fabricated laminate, (d) tested samples, and (e) dimensions of a single cubic sample.