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Effect of microchannels on the crashworthiness of fiber-reinforced composites

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ABSTRACT

The integration of microchannels within structural composites enables a range of multifunctional responses such as thermal management and self-healing. In this work, we investigate how microchannels affect the crashworthiness of the host material. Corrugated panels are fabricated with aligned microchannels (ca. 400 µm diameter) at different channel spacing (10 mm and 1.2 mm), orientation with respect to the loading direction, and alignment with respect to the surrounding fiber-reinforcement. Specific energy absorbed (SEA) is measured by compression testing of samples with a chamfer edge trigger. SEA was preserved within 10% for all test cases. Flat (non-corrugated) panels are also tested to demonstrate that microchannels can serendipitously trigger stable, energy absorbing failure modes that lead to improved crashworthiness. Non-vascular panels without an edge chamfer fail catastrophically when compressed. In dramatic contrast, vascular panels fail in a stable fashion triggered by crack initiation at the microchannels, yielding ca. 10 times more energy absorption.

1. Introduction

Microvascular composites have enabled a variety of multifunctional behaviors including self-healing [1,2], thermal management [3–6], damage sensing [7,8], and electromagnetic modulation [9,10]. However, the presence of vasculature can potentially reduce composite mechanical properties. As recently reviewed by Saeed et al. [11], several studies have characterized how microchannels affect properties such as tensile/compressive strength and stiffness [12–15], fatigue behavior [16], mode 1 and mode 2 fracture toughness [17], low-velocity impact response [18,19], and interlaminar shear strength [20]. Mechanical properties are typically preserved when channel volume fraction is low ($< 2\%$) and channels do not disrupt the continuity or architecture of load-bearing plies.

One property that has not been addressed is the energy absorption of composites in a crash (i.e. crashworthiness), an important design factor for their use in transportation. In a crash, fiber-reinforced composites fail through a combination of compressive failure and splaying (delamination and bending) which leads to material disintegration and high energy absorption [21,22]. The specific energy absorbed (SEA) of carbon-fiber/epoxy composites, i.e. the energy absorbed per unit weight in a crash, ranges from 50 to 100 kJ/kg [23]. For comparison, typical SEA values are ca. 30 kJ/kg for aluminum and ca. 20 kJ/kg for steel [23]. Most of the energy absorbed for a composite derives from compressive failure of the fibers and fracture of the matrix [24]. SEA is increased when using fibers with high compressive strength, or matrices with high interlaminar fracture toughness (which reduces splaying) [25].

Composite crashworthiness is characterized by compressing tubes [26], self-supporting corrugated panels [27–29], or flat panels supported by a fixture [30,31]. Samples are usually manufactured with a damage trigger such as an edge chamfer to prevent catastrophic, low energy-absorbing failure modes such as buckling [32]. Tests are carried out at speeds representative of a crash (ca. 50 km h^{-1}) or under quasi-static loading (1–100 mm min^{-1}) for ease of testing [26]. Quasi-static tests typically provide similar failure modes and SEA values compared to high-speed testing since most thermoset composites are insensitive to strain rate in this regime [33].

While no prior investigations have been performed on how microchannels affect composite crashworthiness, several works report on how channels affect composite compressive strength. Kousourakis et al. [12] compressed carbon/epoxy cross-ply composites with aligned 170 µm–680 µm diameter microchannels at 5 mm interchannel spacing.

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Channels were aligned with the fiber direction in surrounding plies in order to reduce their impact on the natural fiber architecture. Channels oriented with the loading direction caused no reduction in strength for any channel diameter tested. When channels were oriented transverse to the loading direction, a reduction in strength (up to 15%) was attributed to the induced waviness of the surrounding 0° plies and the role of the channels as stress concentrators.

Larger reductions in strength can occur if channels are misaligned with surrounding plies. For example, Huang et al. [13] compressed unidirectional carbon/epoxy composites containing 80 µm–560 µm channels oriented transverse to the fiber (and loading) direction. Strength reduction of 10%–70% was observed, attributed to enhanced ply waviness, channel stress concentration, and the formation of resin pockets around channels. Hartl et al. [14] showed similar strength reductions in simulations of transverse channels in a quasi-isotropic layup. Thus, compressive strength reduces most when channels are oriented transverse to the loading direction, have large diameter, and are misaligned with the fiber direction in surrounding plies.

In this manuscript we report the results of an investigation of the crashworthiness of microvascular carbon/epoxy composites. Two different experimental studies were carried out. First, corrugated cross-ply panels were manufactured containing ca. 400 µm channels at either 10 mm or 1.2 mm interchannel spacing. The 10 mm spacing is representative of microvascular composites used for self-healing [18] and active cooling applications [34], while the 1.2 mm spacing is representative of actively cooled composites designed to operate in hypersonic flight [35]. Crush tests were performed for channels oriented either transverse or longitudinal with the loading direction. The effect of misalignment with the fiber direction of surrounding plies was also investigated. Vascular panels were chamfered and compressed under quasi-static loading to compare failure modes and SEA. Flat (non-corrugated) panels were also tested using a knife-edge fixture. We investigated the use of microchannels to trigger (and guide) failure in a stable fashion to achieve high SEA. Panels were fabricated containing three or five transverse channels located 2 mm from the bottom of the sample, misaligned within surrounding 0° plies. Damage initiation and SEA were compared for samples with no damage trigger, a traditional chamfer trigger, and microchannel triggers.

2. Materials and methods

2.1. Fabrication of corrugated panels with evenly spaced microchannels

A corrugated panel geometry was chosen to allow for compression without buckling (Fig. 1a-b). Dimensions are taken from Grauers et al. [27] and are similar to several other studies on the crashworthiness of corrugated panels [28,29]. Microchannels were incorporated both transverse (Fig. 1c) and longitudinal (Fig. 1d) to the loading direction. Channels were either 400 µm diameter circular channels at a spacing $s = 10$ mm or 430 µm × 330 µm elliptical channels at $s = 1.2$ mm. Channel volume fraction was nominally 0.6% for the 10 mm spacing and 4% for the 1.2 mm spacing.

Transverse channels were incorporated in the midplane of a $[90|0_3|90_2]_S$ layup sequence, resulting in channels aligned with the fiber direction of surrounding plies (Fig. 2a). Longitudinal channels were incorporated into two different layup sequences to produce channels both aligned and misaligned with the fiber direction of the surrounding plies. Channels misaligned with surrounding plies were created in the midplane of the same $[90|0_3|90_2]_S$ layup (Fig. 2b). Channels aligned with surrounding plies were created in the midplane of a $[0|90_3|0_2]_S$ layup (Fig. 2c). Note that this case is equivalent to transverse compression of the transverse channel layup (Fig. 2a).

Panels were fabricated with twelve layers of unidirectional carbon fiber prepreg. The prepreg consisted of Cycom 977-3 epoxy and Hexcel 12K IM7 carbon fiber (190 g m^{-2} fiber areal weight, Cytec-Solvay) with a nominal fiber volume fraction of 61%. An aluminum mold with four sets of corrugations was prepared by electrical discharge machining (EDM), and then prepreg was laid over this mold and placed in a vacuum bag using the manufacturer recommended layup.

The vaporization of sacrificial components (VaSC) technique [10,36,37] was used to form microchannels with well-controlled interchannel spacing. Sacrificial preforms of polylactide (PLA) infused with 3 wt% tin oxalate (SnOx) catalyst were placed between the 6th and 7th prepreg layers during layup. PLA fibers of ca. 400 µm diameter (CU Aerospace) were used for $s = 10$ mm, while 3D-printed PLA strips of ca. 430 µm × 330 µm cross-section were used for $s = 1.2$ mm. The strips were printed with a TAZ6 fused deposition modeling printer (Lulzbot) using PLA filament (CU Aerospace) extruded at 170 °C through a 0.35 mm diameter nozzle at 500 mm/min speed, 0.38 mm print height, and 60 °C bed temperature.

For samples with transverse channels at $s = 1.2$ mm, butyl rubber pressure strips (3.2 mm thick, Airtech) were added above the final prepreg layer to provide additional compaction during cure. This step was added since these samples otherwise compacted poorly and contained voids. Laminates were cured in an autoclave at 130 °C for 4 h and 160 °C for 3 h (2 °C min^{-1} ramps) under 640 kPa external pressure and vacuum (ca. 50 torr). Panels were then cut to size using a diamond saw and VaSC treated at 200 °C for 32 h and vacuum (ca. 1 torr) to vaporize the PLA [36].

Channel morphology was characterized using a digital microscope (Keyence VHX-5000). Transverse channels aligned with the fiber direction of surrounding plies packed well within surrounding fibers and showed dimensional stability (Fig. 2d-e). In contrast, longitudinal channels misaligned with the fiber direction of surrounding plies were surrounded by a large resin pocket and were significantly compressed during cure (Fig. 2f-g). Circular (ca. 400 µm) PLA fibers at $s = 10$ mm gave rise to ca. 600 µm × 300 µm channels with discrete resin pockets (Fig. 2f), while 3D-printed PLA at $s = 1.2$ mm led to ca. 700 µm × 200 µm channels with continuous resin pockets between channels (Fig. 2g). Longitudinal channels aligned with the fiber direction of surrounding plies had similar morphology to transverse channels (Fig. 2h-i).

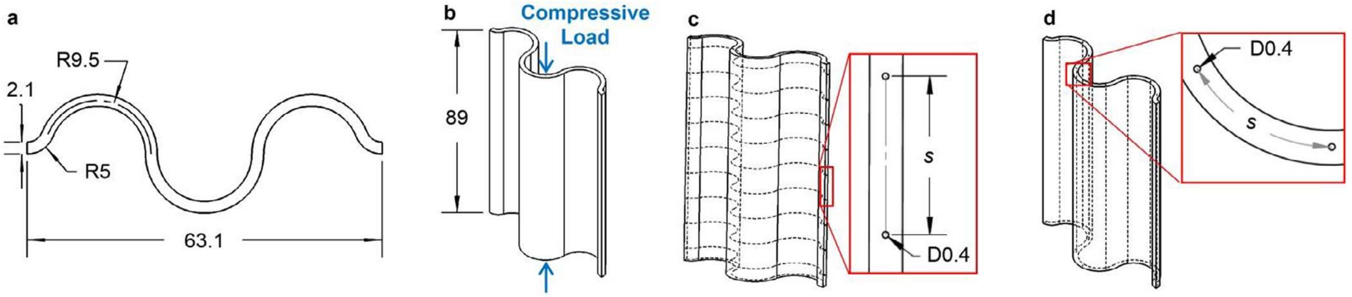

Fig. 1. Geometry of microvascular corrugated panels. a–b) Top and isometric view of panel with dimensions in mm. c–d) Schematics of compression panels with c) transverse and d) longitudinal channel orientations. The channels shown are 0.4 mm diameter with a spacing s of 10 mm. Panels were also fabricated with a denser network of 430 µm × 330 µm channels at $s = 1.2$ mm.