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Dynamic constitutive response of novel auxetic Kevlar®/epoxy composites

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ABSTRACT

A comprehensive experimental investigation was performed to study the dynamic compressive constitutive response of novel auxetic Kevlar®/epoxy laminated composites. Strain rate response was investigated using the split Hopkinson pressure bar (SHPB) test setup. Laminated composites were fabricated using the vacuum infusion process. Short Nylon fibers were flocked between the laminates with different flock densities and flock length. For obtaining dynamic force equilibrium in SHPB experiments, a copper pulse shaper was used to increase the rising time of incident pulse. To have a comparison, woven Kevlar®/epoxy composites were also characterized at similar strain rates. In addition, quasi-static tests were also performed on both woven and auxetic laminated composites for completeness of the study. For quasi-static loading conditions, auxetic composites showed higher peak strain and lower peak stress compared to woven composites. For non-flocked composites, both auxetic and woven composites showed rate dependency. Woven composites provided 353% increase in peak stress when the strain rate increased from 1200 s^{-1} (low) to 3300 s^{-1} (high). However, in the same conditions, auxetic composites showed only 155% increase in peak stress. For different flocking conditions, woven composites showed rate dependency for all strain rates, but auxetic composites demonstrated rate dependency only from low to medium strain rates. Both auxetic and woven composites experienced shear failure under quasi-static compression, where auxetic composites failed at higher shear angle of 37°, but woven composites had a failure angle of 30°. For impact loads, under no flocking condition, woven composites did undergo severe edge failure at all strain rates, but auxetic composites showed a sign of edge failure only at high strain rates. With the flocking condition, auxetic composites had through thickness shear failure and woven composites experienced splitting and fibrillation of Kevlar® fibers.

1. Introduction

In the recent past, the employment of fiber-reinforced polymer composites in engineering structures has been increasingly diversified from sports equipment to high performance racing cars, navy ships, helicopters, and aeroplanes. Although there are several kinds of fibers used in laminated composites, Kevlar® has been used widely due to its light weight, tensile strength, toughness, and resistance to impact damage [1]. A significant amount of research has been reported to understand the mechanical behavior of woven Kevlar® composites under impact loading conditions. To start with, Kinari et al. [2] performed dynamic tension test on Kevlar® 29 yarn at different strain rates up to 1000 s^{-1}. They showed that peak load and peak modulus increased with strain rate, although the percentage of elongation at breaking point decreases. Later, Zhu et al. [3] investigated quasi-static and dynamic penetration by cylindro-conical projectiles on woven Kevlar®/polyester laminates of varying thicknesses. The force-deflection curves of indentation were found to be highly sensitive to the size of the projectiles and the tip angle. In addition, they identified quite different damage patterns under dynamic loading when compared to quasi-static penetrations. Rodriguez et al. [4] studied the influence of strain rate on the mechanical properties of aramid and polyethylene woven fabric composites. They observed differences in the stress-strain response of both static and dynamic testing and indicated that strain rate significantly influenced the longitudinal strength and failure strength of the composites. Viswanathan et al. [5] performed an experimental study to determine mechanical properties of Kevlar® 29/Polyethylene thermoplastic composites in compression at high strain rates using the split Hokinson pressure bar (SHPB) technique. They were able to fabricate composites with very high volume fraction of 85% and noticed significant increase in compressive yield strength as well as decrease in yield strain at high strain rates when compared to quasi-static experiments.

Wang and Xia [6] obtained stress-strain curves of Kevlar® 49 aramid

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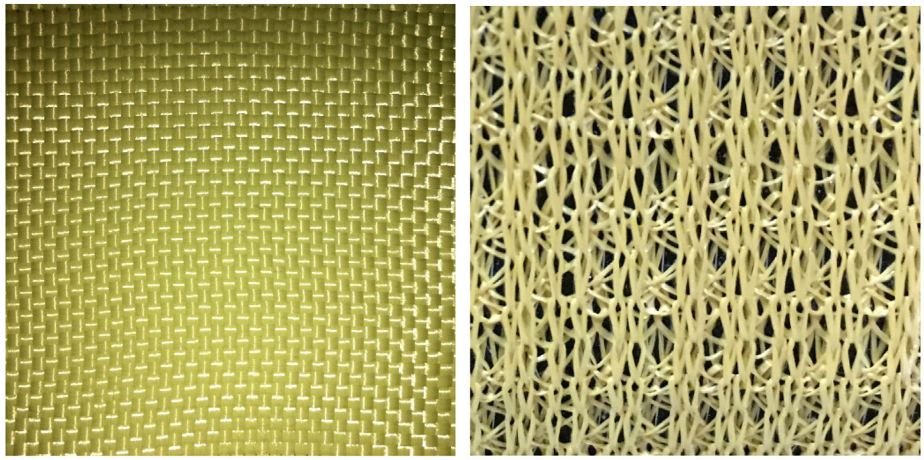

Fig. 1. (a) Woven Kevlar, (b) Warp knitted auxetic Kevlar® fabric.

fiber bundles under both quasi-static loading and high rate loading up to 1000 s^{-1}. Their experimental results showed that Kevlar® 49 fiber demonstrated sensitivity to strain rate. The peculiar "skin-core" structure of Kevlar® aramid fiber and experimental Weibull data confirmed that there were two types of fracture modes in Kevlar® fiber. Later, they validated the application of bimodal Weibull distribution for their experimental data. Following this validation, the same authors, Wang and Xia [7] discussed the effect of both strain rate and temperature on the tensile properties of Kevlar® 49 fiber bundles under impact tensile loads. It was found that the tensile mechanical properties of Kevlar® 49 fiber bundles depended on both the strain rate and the temperature. They again employed a bimodal Weibull distribution statistical model of the strain rate and temperature dependence of fibers and determined Weibull parameters of fibers from the fiber bundle test.

Kang and Kim [8] made a comparison of multiaxial warp-knit fabric (MWK) and regular Kevlar® woven laminates by performing impact studies. It was found that the multiaxial warp-knit composite had higher impact fracture toughness and bending properties that resulted in smaller damaged regions compared to Kevlar® woven laminates. Tan et al. [9] studied the mechanical behavior of aramid fibers at high strain rate with the SHPB. They utilized a viscoelastic material model to describe the mechanical behavior of the yarns and fracture modes. They employed the same material model in the computational simulation of ballistic penetration of woven aramid fabrics. A comparison of the simulations and actual ballistic tests showed that predictions of the energy absorbed by the fabric were in good agreement with the experiments. Reis and Ferreira [10] performed impact tests on Kevlar® composites filled with epoxy matrix. For improving the impact response of composite, they added two different fillers: nanoclays Cloisite 30B and cork powder. Nanoclays promoted higher maximum impact loads, lower displacements, the best performance in terms of elastic recuperation, and the maximum residual tensile strength. Woo et al. [11] reported that by increasing the strain rate in the range of 1182–1460 s^{-1}, the peak stress and toughness of woven Kevlar®/epoxy composites increased by two times. In addition, they also used acoustic emission to determine the failure modes of composites. Kapoor et al. [12] investigated the dynamic response and failure mechanism of Kevlar® reinforced Polypropylene composites. They reported that the fracture toughness increased almost ten times and the peak stress increased by three times with the increase of strain rates from 1370 to 6066 s^{-1}. The addition of maleic anhydride–grafted polypropylene (Mag-PP) improved the interfacial properties of composite, which resulted in increasing the peak strain by two times. Nayak et al. [13] presented results from both experiments and numerical simulations on ballistic impact of aramid-epoxy composite laminates by an armor piercing projectiles at various impact velocities. They also employed a high-speed video camera to capture the interaction on projectile with composite laminates. The magnitude and duration of stress as well as the contact force was found to increase when the projectile impacted at lower velocities. This enhanced the extent of delamination and the core damage area. However, the trend was reversed for higher impact velocities. Recently, Yang et al. [14] investigated fracture performance of auxetic Kevlar® composites against woven counterparts. It was reported that auxetic Kevlar® composites demonstrated 225% increase in fracture toughness and showed crack arrest and branching mechanisms when compared to woven Kevlar® composites for similar conditions.

As discussed above, all studies are reported on regular woven Kevlar® laminated composites. There are no studies reported on dynamic constitutive response of auxetic Kevlar® laminated composites. Motivated by very significant improvement in fracture toughness [14] of auxetic Kevlar® composites as mentioned above and their flexibility to conform to shape, in this study, an experimental study was conducted to understand the dynamic compressive constitutive performance of auxetic Kevlar® laminated composites. To have a valid comparison, regular woven Kevlar® composites were also fabricated and characterized. Although quasi-static compression experiments were also conducted in this study, they are not comparable with dynamic experiments; they were performed for completeness. In addition, z-axis reinforcement through short Nylon fiber flocking was employed to investigate the effect of various flocking parameters on dynamic stress-strain response using SHPB.

2. Experimental conditions

2.1. Materials

To fabricate the composites, warp knit structured novel auxetic Kevlar® fabrics with 200-denier, patented by University of Massachusetts Dartmouth (UMASSD) technology, was used as a reinforcement. Fig. 1(b) shows the image of warp knitted auxetic Kevlar® fabric [15]. To compare with auxetic Kevlar® composites, woven Kevlar® with plain weave pattern were also used in this study (shown in Fig. 1(a)). The 2000/2120 (1.15 g/cm^3 and 0.95 g/cm^3) series amine-cured epoxy resin system, supplied by FiberGlast (Brookville, OH), mixed with mass ratio of 30:100 (hardener to resin) was used as matrix material. 3-denier short Nylon fiber with two different flock lengths (0.76 mm, and 1.2 mm long) and two different densities (200 flock/mm^2 and 600 flock/$mm^{2)}$, provided by Claremont Flock Inc. (Leominister, MA), were used for z-axis reinforcement. The short fiber z-direction flocking technique was used to normally implant to the laminate