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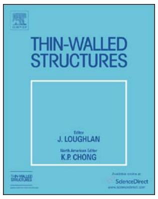

Full length article

Numerical and experimental investigations into the response of STF-treated fabric composites undergoing ballistic impact

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ABSTRACT

This paper deals with the experimental and numerical investigation of the impact resistance properties of woven high modulus polypropylene (HMPP) fabrics impregnated with shear-thickening fluids (STFs) composed of fumed silica nanoparticles suspended in polyethylene glycol (PEG). The impact of ogival tip projectile on four-layered fabrics was simulated using LS-DYNA®. One important issue addresses the effect of STF impregnation on improving the ballistic properties of woven fabrics. The effect of STF impregnation on fabric are taken into account as the friction between the yarns and their crossovers and the friction between projectile and fabric during impact. Comparing the depth of indentation of samples with the corresponding experimental data reveals acceptable agreement between the results of the computational analysis and experiments. Both the numerical and experimental investigations on the impact resistance of neat and STF-treated HMPP fabric confirmed the contribution of frictional properties induced by STF impregnation in restriction of the yarns within the fabric.

1. Introduction

Woven fabrics made from light weight and high strength fibers are often used in a wide-range of applications such as protective materials and body armor for military [1,2]. However, they offer a limited level of protection against ballistic threats, especially without reinforcement metal or ceramic plates. According to the literature, the ballistic and stab resistance performance of woven fabrics could be improved by impregnation of the fabric with a shear-thickening fluid (STF) [3–6]. The STF is a non-Newtonian fluid that under the high-speed impact situation, their viscosity increases dramatically. In other words, when it encounters high-speed shear rate, the drastic increase in its viscosity leading to the transformation of state of matter from liquid suspension to semi-solid. The rheological behavior of STFs are influenced by several parameters including the particle volume fraction, particle shapes and sizes, preparation methods, temperatures, surfactants, fillers and additives, and properties of continues phase [7–10]. Shear-thickening behavior has gained special interest for both scientific and technological issues and finding applications in improving ballistic and stab resistance performance of soft body armors. A great deal of studies have been focused on the improved impact resistance performance of textile structures by application of STFs to high performance fabrics such as Kevlar®, Dyneema®, and Twaron® [11–14]. For instance, Lee et al. [15] have investigated the ballistic performance of Kevlar fabrics impregnated with STFs and found that the ballistic performance in terms of absorbed energy is more than double. In other words, four layers of STF/Kevlar composite absorbed as much energy as ten layers of neat Kevlar. This property has created special interest towards improving the impact resistance performance of textile structures by application of STFs to fabrics.

From a technological point of view, the ballistic and impact resistance performance of STF-treated fabric composites is controlled by a variety of parameters. Despite the surge in attention to the STF-treated fabric composites, a few investigations have addressed the quantitative study of the effects of the parameters which has hindered the performance of system and also the simulation of the response of STF-treated samples subjected to ballistic impact [16,17]. Hence, the present study aims to investigate the ballistic performances of neat and STF-treated high modulus polypropylene (HMPP) fabrics subjected to high-velocity impact test. The backside deformation of specimens and back face signature on the clay witness are analyzed experimentally and numerically. First, the tensile and yarn pull-out tests are performed to the samples to get the mechanical properties of neat and STF-treated fabrics. Then, the ballistic test is carried out using ogival tip projectile to assess the ballistic resistance performance of HMPP fabric after impregnating with STF. A finite element code LS-DYNA is also used to

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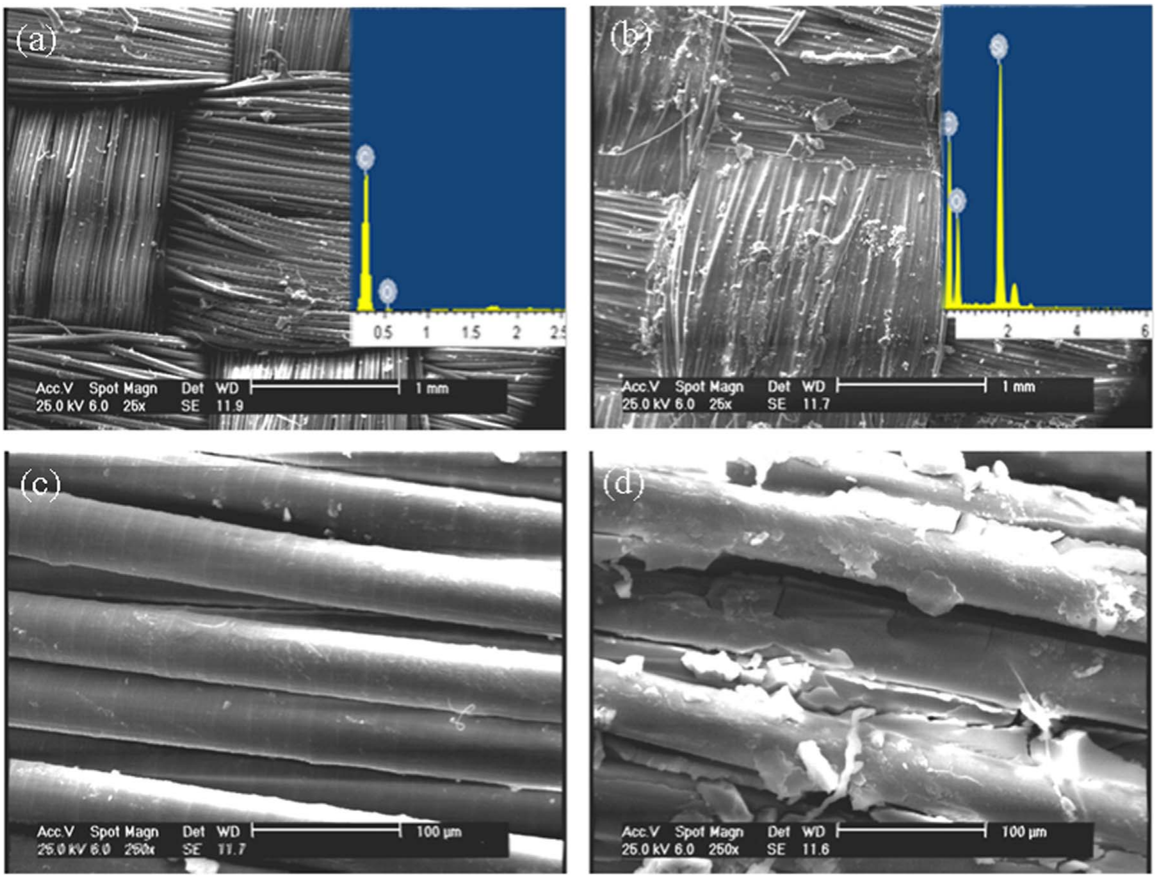

Fig. 1. SEM micrographs for neat (a, c) and STF-treated (b, d) HMPP fabrics.

simulate the behavior of four-layer STF-treated HMPP fabric under ballistic impact load.

2. Experiments

2.1. Materials and methods

High modulus polypropylene (HMPP, e.g., Innegra™) fabric was purchased from Colan (Australia) and has been used in the experiment. Shear-thickening fluid, which is composed of fumed silica nanoparticles dispersed in Polyethylene glycol (PEG), was prepared as described by previous research [18]. STF-treated HMPP fabric composite were prepared by impregnation of STF into the fabrics. First, STF diluted with ethanol in proportion of 1:3 (STF: ethanol) to facilitate the impregnating process by reducing the surface tension and viscosity of STF. The HMPP fabric was soaked in the STF/ethanol containing bath for 5 min and then were padded with a pressure of about 1 bar to wet pickups of about 80%. Finally, they were put into the drying oven at 80 °C for 20 min to evaporate the added ethanol from samples. The SEM micrographs of STF-treated fabrics have been shown in Fig. 1.

2.2. Mechanical characterizations

The specimens were first subjected to uniaxial tensile test to obtain mechanical properties. It was performed using an INSTRON 5566 Universal Testing Machine (USA) equipped with a 10 kN load cell at the crosshead speed of 70 mm/min. The obtained results are shown in Table 2. Yarn pull-out test was also carried out on the samples to understand the effect of STF on the inter-yarn frictional behavior of fabric. The fabric dimensions for performing the pull-out test were 50 and 90 mm in width and length, respectively and the testing speed was 100 mm/min. The samples were clamped under no pre-tension and were pulled-out in the warp and weft directions (Fig. 2).

Table 1
Material properties of HMPP fabric and projectile.

Sample	Properties	Values
HMPP fibers[a]	Young's modulus	$E_{11} = 17$ GPa $E_{22} = E_{33} = 8.5$ GPa
	Shear modulus	$G_{13} = G_{12} = G_{23} = 8.5$ GPa
	Poisson's ratio	$\nu_{12} = \nu_{13} = \nu_{23} = 0$
	Density	$\rho = 0.67$ g/cm^3
Projectile	Young's modulus	$E = 210$ GPa
	Poisson's ratio	$\nu = 0.3$
	Density	$\rho = 7.85$ g/cm^3

[a] the mechanical properties of HMPP fibers has been used for numerical simulation.

Table 2
Tensile strength and strain for the neat and STF-treated HMPP fabrics.

Sample	Tensile strength (MPa)		Tensile strain (%)	
	warp	weft	warp	weft
Neat HMPP fabric	104.5	106.0	34.2	22.5
STF-treated HMPP fabric	117.6	109.6	33.3	20.8

2.3. Ballistic impact test

High-velocity impact tests were carried out by using a gas gun powered by high-pressure nitrogen gas based on the standards of the National Institute of Justice (NIJ-0101.04) ballistic test setup [19]. The backside deformation of specimens and back face signature on the clay witness were analyzed to access the ballistic impact test. The fixture