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Numerical simulation of the impact behaviors of shear thickening fluid impregnated warp-knitted spacer fabric

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ABSTRACT

The impact behavior of warp-knitted spacer fabrics (WKSFs) impregnated with shear thickening fluid (STF) under low-velocity impact loadings have been investigated from experimental and finite element analyses (FEA) approaches. From the experimental approach, the impact load–displacement curves have been obtained. It was observed that the WKSF impregnated with the STF composite material (the WKSF/STF composite) shows a higher stiffness and lower peak force than those of the WKSF under the same impact loadings. In FEA approach, the geometrical models of the WKSF and the WKSF/STF composite material were established based on the WKSF fabric architectures. The dynamic responses including the impact load–displacement curves and impact deformation of the samples were predicted based on finite element analyses at the microstructure level. It was found that the STF and the coupling effect between the STF fluid and fiber tows are the key factors which influence the cushioning behaviors of the composite. The energy absorption mechanisms include the buckling of the spacer finer tows and the thickening effect of the STF under impact loading. The WKSF/STF composite could be expected as a damping or energy-absorptive materials under impact loading.

1. Introduction

Warp-knitted spacer fabrics (WKSF) are three-dimensional fabrics consisting of two separate fabric layers connected vertically with pile yarns. Due to their unique structure, WKSF has several advantages: low weight, high production, high permeability and excellent energy absorption. In recent years, WKSF can be used as advanced materials in the following areas: automotive, geotextiles, sports, safety and protection and so on [1–5]. However, in these applications, the spacer yarns in the fabric are easily buckled and the energy absorbed by spacer fabric is limited. So WKSF require using a material which can change its mechanical property depending on the loading conditions. Such behavior is characteristic of shear thickening fluids (STFs). STFs are a non-Newtonian fluid, which shows drastic rise in viscosity beyond a critical shear rate [6]. In recent years, the application of shear thickening fluid (STF) impregnated fabric have gained the attention of scientists because of its excellent energy absorption capability [7].

The compressive properties and other behaviors of WKSF have been discussed by several researchers. Yip et al. [8,9] studied the physical and mechanical properties of three-dimensional spacer fabrics and molding properties for intimate apparel application. Liu et al. [10,11] studied the quasi-static and impact compressive behavior of WKSF for protective applications. They found that all the structural parameters have effects on compressive behavior and cushioning performance of WKSF. Lee et al. [12] studied the rheological properties and ballistic impact characteristics of STF impregnated woven Kevlar fabrics; the ballistic resistance improved significantly and the fabric did not loss any flexibility. Park et al. [13,14] found that the fiber count, shot location and the laminating sequence affected the ballistic performance of aramid fabrics impregnated with shear thickening fluid. The stab resistant property of STF impregnated fabric was studied by Decker et al. [15] and Kang et al. [16,17]. From their findings, the stab resistance of STF impregnated fabric improved significantly. Dawson and Gibson [18] studied the dynamic compressive response of the open-cell foam impregnated with non-Newton fluid, a analytical lubrication model for squeezing flow of a non-Newtonian fluid between two parallel plates was developed to analysis the effects of material parameters on the response of a NNF-filled foam under dynamic loading. The compressive properties of WKSF impregnated with STF were investigated by the authors [19].

To use WKSF efficiently and reasonably, it is essential to be able to accurately predict and model the mechanical and structural

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response of the composite materials in order to optimize their usage. In the past decades, several efforts had been made to numerical simulation the deformation mechanisms of 3D fabric. Sadighi and Hosseini [20] investigated the mechanical behavior of three-dimensional woven glass-fiber sandwich composites using FE method. Renkens and Kyosev [21] presented a method to generate complex 3D warp knitted structures based on single bed topology. Guo et al. [22] investigated the compression behaviors of the spacer fabric using the theoretical model. Vassiliadis et al. [23] developed a finite element model for 3D spacer fabric to investigate the compression performance by two-scale (micro and macro). The effect of the structural and physical parameters of the sample on the compression resistance was analyzed by the model. Hou et al. [24] studied the computational mechanical of a typical 3D spacer fabric. They used the Micro X-ray computed tomography to determine a precise geometry of the spacer fabric, and seven FE model was used to analysis the compression mechanism.

Currently, few studies have been done on numerical modeling the mechanical properties of the spacer fabric impregnated with STF (the WKSF/STF composite material). In this paper, the impact behaviors of STF impregnated WKSF under low velocity impact loadings will be reported using finite element analysis (FEA) method. The WKSF/STF composite were modeled in the commercial software ABAQUS/Explicit using 3D geometrical model based on the real microstructures. The fiber tows were assumed as elastic–plastic solid, and the STF was assumed as power-law fluid. Results from impact tests have been employed to validate the model. Additionally, the impact process and the deformation morphology will be presented. Finally, the deformation and energy absorption mechanism will be discussed.

2. Materials and tests

2.1. STF impregnated WKSF

The composite material discussed in this paper was made of the warp-knitted spacer fabric impregnated with STF. A typical WKSF was produced on a GE296 high speed double-needle bar Raschel machine with six yarn guide bars (Wuyang Warp Knitting Machine Ltd., Changzhou, Jiangsu, China). The polyester multifilaments were used to create the binding of the structure in the knitting process through GB1, GB2 for the top outer layer and GB5, GB6 for the bottom outer layer. The polyester monofilaments were used as spacer yarns to connect the two outer layers together through guide bar GB3 and GB4. The lapping movements of guide bar as below:

GB3: 1-0 3-2/3-2 1-0//half threaded.
GB4: 3-2 1-0/1-0 3-2//half threaded.

The specifications of the WKSF are listed in Table 1. The top surface and cross-section photographs of the WKSF are shown in Fig. 1(a) and (b) respectively.

Table 1
Specifications of WKSF.

Parameters	Value
Monofilament diameter (μm)	0.2
Multifilaments (D/F)	300/96
Warp-wise density (source/cm)	7.15
Weft-wise density (wale/cm)	5.72
Outer layer thickness (mm)	0.2 ± 0.2
Whole thickness	10 ± 0.1

The STF components included nano-particles and carrier. The fumed silica used was Aerosil D200 (Degussa Corporation, Akron, OH), which has a primary particle size of 12 nm and a specific surface area of approximately 200 $m^2\,g^{-1}$. Polyethylene glycol (PEG) (Sinopharm Chemical Reagent Co., Ltd.) was chosen as a solvent. Each suspension was prepared by adding the silica to the PEG in a blender and mixed for 2 h. The samples were then placed in a vacuum chamber at room temperature for about 24 h to remove the bubbles.

An equal volume of ethanol was added to the original ethylene glycol based the STF. The diluted STF easily impregnated the fabric. Following impregnation, the composite was heated in a convection oven at 60 °C for 8 h to remove the ethanol from the sample. Then the excess STF of outer spacer fabric were removed. The WKSF/STF composite system and the WKSF fabric are shown in Fig. 1(c).

2.2. Rheological tests

Rheological measurements were performed with Rheometrics ARES-RFS (TA Instruments-Waters LLC). A parallel-plate with the diameter of 20 mm was used for the measurement with the temperature controlled at 25 °C. In this study, the steady-state strain rate sweeps and frequency sweeps were conducted to study the rheological properties of the STF.

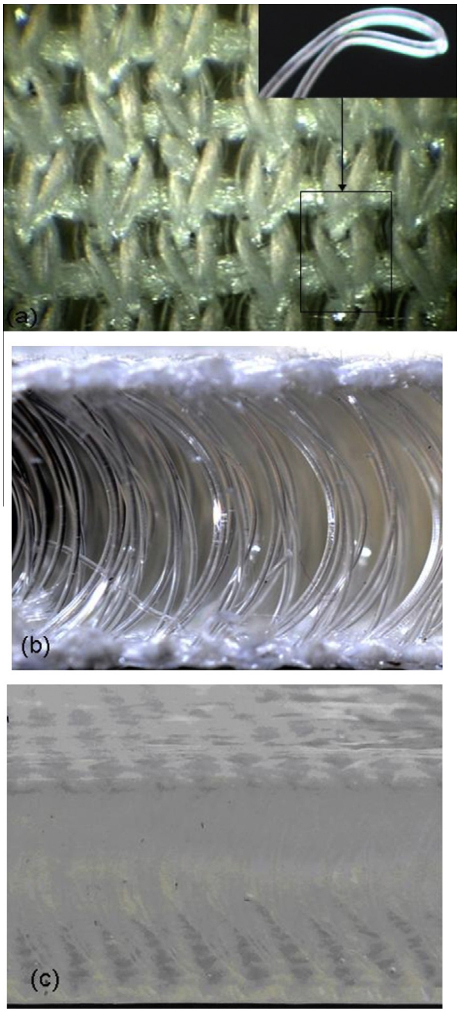

Fig. 1. Photograph of specimen of WKSF and composite materials.