Finite-element Simulation of Kevlar Yarns and Fabrics in Assessing its Mechanical Protective Performance under Projectile Impact Loading

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Abstract: With the increasing concern on occupational safety, people pay more and more attention to mechanical protection. At present, the focus of relevant researches is on the mechanical protection performance of high-performance fibres and high-strength fabrics. The influences that mechanical properties of fabrics have on the mechanical protective performance of clothing are discussed in this paper. Woven fabrics made of high-performance fibres have been widely used as mechanical protective clothing in the form of flexible armour such as bullet-proof vests, stab-resistant garments and so on. The mechanical response and energy absorption characteristics of fabrics under high-speed projectile impact are dependent upon intrinsic constitutive relations, construction parameters such as fabric type, fabric construction, areal density, projectile shape, and impact conditions such as impact velocity and boundary conditions.This project involves the study of Kevlar fibre which is a poly-p-phenylene terephthamide (PPTA) fibre. The Kevlar fabric studied in this paper is plain woven. Experiments about construction parameters of Kevlar yarns are proposed to obtain the mechanical properties of woven fabrics. This paper also investigates the finite-element simulation of huge impact on Kevlar fabric by proposing a material model, which incorporates stretch and elasticity restoring property and failure criteria. A non-linear, explicit, three-dimensional finite-element program ANSYS is used to simulate the response of fabric to high-speed projectile impact with two Hookean springs and a Newtonian dashpot.

Keywords: Finite-element modeling, mechanical protective clothing, ballistic impact, energy absorption.

1. Introduction

Woven fabrics made from high-strength fibres have been widely used as protective equipment to reduce mechanical damage, such as bullet-proof vest, aramid helmets and reinforcing layers in composite structures. A fiber called Kevlar which is the most commonly known among mechanical protective products is studied in this paper. Kevlar fabrics are made of highly oriented poly- p- phenylene terephthamide.

For the sake of designing protective products using woven fabric, the performances of high-strength fabric to a greater impact should be considered. The impact response and energy absorption characteristics of fabric under impact loading are dependent on the construction parameters of the fabric such as properties of the material, fabric construction, areal density, and impact conditions including projectile shape, impact velocity and boundary conditions.

To analyze the mechanical performances of protective clothing in detail , experiments were designed to obtain the properties of yarns and fabrics. The tensile parameters of yarns have been studied with the INSTRON testing equipment. The yarn's elasticity modulus, elastic elongation ratio, elastic potential energy would be obtained in this tensile strength test. An impact experiment was designed to study the energy absorption and deformation of yarns and fabrics under different velocities.

As a cost-effective method, theoretical and finite-element modeling is useful to determine the response of a fabric to an impact with these parameters. Numerical models for predicting the performance of mechanical protective products have been the subject of interest in defense as well as commercial industries for many years. However, the impact conditions of fabric are complex. Most models attempt to provide the most accurate simulation of the impact performance. In this paper, the models of yarns and fabrics would be established to achieve the computational simulations with parameters from various experiments.

A non-linear, explicit, three-dimensional finite-element code ANSYS is used to simulate the response of yarn and fabric to various impacts under different velocities. The yarn and fabric are modeled by membrane elements with suitable material properties to account for the characteristics. The deformational profiles of the fabric at different times corresponding to different impact velocities are also investigated. The results obtained from computational simulations are verified with that of experiments. Finally, limitations arising from the approaches taken are discussed in this paper.

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2. The properties of woven kevlar fabric

The woven fabric investigated in this paper is made from high-strength fibers namly Kevlar 964C.[11] The highly oriented polymers of this fiber endow it with many excellent physical and chemical characteristics.

Kevlar fiber is made of poly-p-phenylene terephthamide (PPTA) which is the simplest polyamide of AABB contrapuntal directional form. The all-para aromatic polyamide is obtained from polycondensation of para-Phenylenediamine and paraphthaloyl chloride. Because of the rigidity of molecular chains and the crystallization of the solution， aeolotropic microstructure could get under large shear stress in the solution. The glass-transition temperature of Kevlar is over 300℃. The decomposing temperature is 560℃. When staying in air at 180℃ for 48 hours, the strength retention rate is 84％. Kevlar fiber has high tensile strength of 0.215 $N/dtex$ and high initial elastic modulus of 4.4～8.8 $N/dtex$. Its strength ratio is five times that of steel. Kevlar fibers are often used in composite materials to resist strain, stress and flexural strength. Their properties of heat-shrinking and creep are both stable. Otherwise, the electrical insulation and chemical resistance are also high.

Table 1 Properties of projectile and fabric

Properties	Projectile	Kevlar fabric
Material type	rigid	plastic kinematic
Density (g/cm3)	7.8	1.44
Modulus (GPa)	200.0	71.00
PRXY	0.3	0.20

The tensile behavior and strain rate of Kevlar 964℃ are both related to the temperature. [11] The tensile impact experiments were carried out at different strain rates and temperatures were measured using Hopkinson bar-bar tensile impact apparatus. At the same temperature, the failure stress, unstable strain, initial elastic modulus and specific fracture strain energy density increase with increasing strain rate. At the same strain rate, the failure stress, unstable strain and specific fracture strain energy density increase with increasing temperature, but initial elastic modulus decreases with increasing temperature. The results obtained by Mao et al. are plotted in Figures 1 and 2.

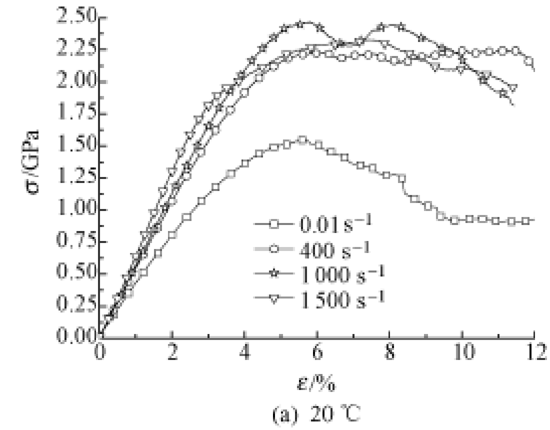

Figure 1 Stress - strain curves of Kevlar under different strain rate at 20℃

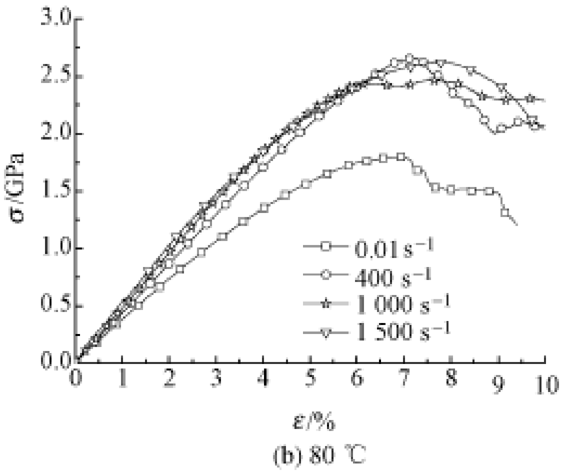

Figure 2 Stress - strain curves of Kevlar under different strain rate at 80℃.

Like most of the polymers, the viscoelasticity of Kevlar plays an important role on the impact issue. Figure 3 shows the relationship between various properties of Kevlar. To tailor the woven fabric to the exact requirements of its functions, it is necessary to determine its impact response. The impact response and energy absorption characteristics of fiber and fabric under impact loading are dependent upon constitutive relations and construction parameters such as fabric type, fabric construction, areal density, projectile shape, as well as impact conditions such as impact velocity and boundary conditions. The properties of projectile and fabric are listed in Table 1.