International Journal of Solids and Structures 51 (2014) 2504–2517

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

On the transverse compression response of Kevlar KM2 using fiber-level finite element model

Subramani Sockalingam [a,b,*], John W. Gillespie Jr. [a,b,c,d], Michael Keefe [a,b]

[a] Center for Composite Materials, University of Delaware, DE, USA
[b] Department of Mechanical Engineering, University of Delaware, DE, USA
[c] Department of Materials Science and Engineering, University of Delaware, DE, USA
[d] Department of Civil and Environmental Engineering, University of Delaware, DE, USA

ARTICLE INFO

Article history:
Received 12 November 2013
Received in revised form 10 February 2014
Available online 26 March 2014

Keywords:
Aramid fiber
Tow
Finite element analysis (FEA)
Micro-mechanics
Transverse compression

ABSTRACT

Flexible textile composites like woven Kevlar fabrics are widely used in high velocity impact (HVI) applications. Upon HVI they are subjected to both longitudinal tensile and transverse compressive loads. To understand the role of transverse properties, the single fiber and tow transverse compression response (SFTCR and TTCR) of Kevlar KM2 fibers are numerically analyzed using plane strain finite element (FE) models. A finite strain formulation with a minimum number of 84 finite elements is determined to be required for the fiber cross section to capture the finite strain SFTCR through a mesh convergence study. Comparison of converged numerical solution to the experimental results indicates the dominant role of geometric stiffening at finite strains due to growth in contact width. The TTCR is studied using a fiber length scale FE model of a single tow comprised of 400 fibers transversely loaded between rigid platens. This study along with micrographs of yarn after mechanical compaction illustrates fiber spreading and fiber–fiber contact friction interactions are important deformation mechanisms at finite strains. The TTCR is also studied using homogenized yarn level models with properties from the literature. Comparison of TTCR between fiber length scale and homogenized yarn length scale models indicate the need for a non-linear material model for homogenized approaches to accurately predict the transverse compression response of the fabrics.

1. Introduction

Kevlar aramid fibers based on poly (para-phenylene terephthalamide) (PPD-T) (Yang, 1993) are widely used in high velocity impact (HVI) applications such as soft body armor (Kim et al., 2008) and gas turbine engine containment system (Sharda et al., 2006) due to their high specific strength, modulus and energy absorbing properties. Other applications include ropes and cables, tires and rubber goods (Yang, 1993), aerospace (DuPont, 2013) and cut-resistant clothing (Yang, 1993). Continuous fibers are typically used in the form of textile fabrics. The textile fabrics possess a hierarchical structure with different length scales from fibers to yarns to woven fabrics. Textile fabrics can be woven from yarns in many different styles (e.g. in Dong and Sun (2009) list five different styles of plain woven Kevlar fabrics using different Kevlar fibers with their axial modulus). A yarn (tow) consists of a bundle of minimally twisted individual fibers with filament counts in the range of 100–10,000 (e.g. a Kevlar KM2 yarn consists of 400 individual filaments).This multiscale architecture as shown in Fig. 1 poses a challenge in modeling and predicting accurate mechanical and impact behavior.

In the continuum finite element (FE) modeling space flexible Kevlar fabrics are modeled using various approaches such as orthotropic continuum at yarn length scale (Duan et al., 2005; Rao et al., 2009a), unit cell based homogenized model using membrane/shell elements (Grujicic et al., 2010; Stahlecker et al., 2009) and multiscale global/local approach with yarn and fabric length scales (Nilakantan et al., 2010; Rao et al., 2009b). For the yarn-level models all the Poisson's ratios are assumed to be zero and the transverse modulus are assumed to be very small compared to the longitudinal modulus to represent the thread like yarn behavior (Gasser et al., 2000). These continuum approaches do not accurately account for transverse compression response of tows where fiber compression, fiber–fiber contact and friction and fiber spreading within the tow are important physically observed deformation mechanisms (Nilakantan, 2013).

* Corresponding author at: Center for Composite Materials, University of Delaware, DE, USA. Tel.: +1 302 831 1283; fax: +1 302 831 8525.
E-mail address: sockalsi@udel.edu (S. Sockalingam).

http://dx.doi.org/10.1016/j.ijsolstr.2014.03.020
0020-7683/

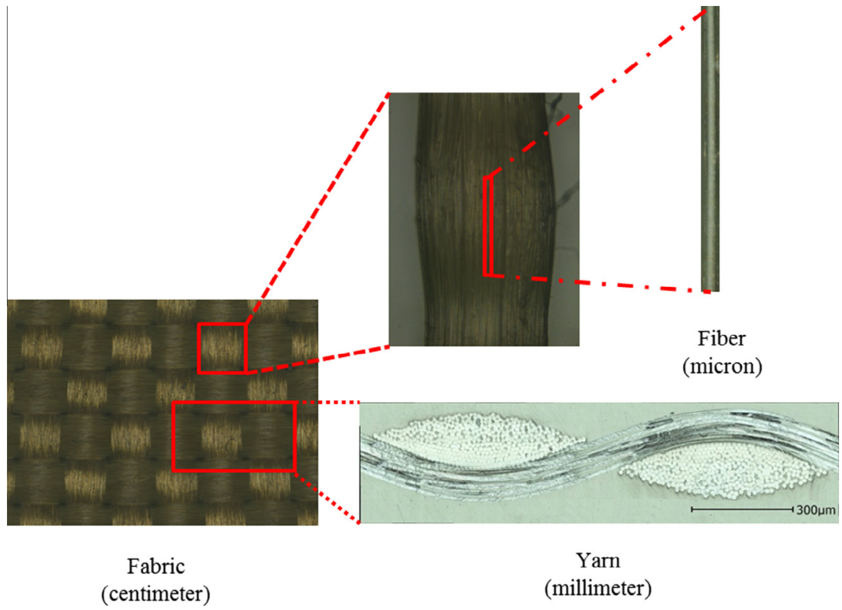

Fig. 1. Optical images of Kevlar K706 fabric and yarn cross section with KM2 fibers.

At the fiber length scale Durville (2008) developed an enriched kinematical 3D beam model to represent deformation of the fiber cross section considering contact and friction between the fibers. Wang et al. (2010) developed digital element method to simulate the ballistic impact of textile fabrics wherein the yarn is represented as an assembly of digital fibers using 1D rod elements connected by frictionless pins. They used contact elements to model contact between the fibers, the contact stiffness for fiber–fiber compression being calculated using the fiber transverse modulus. They used 1, 7, 14 and 19 digital fibers (diameters varied to conserve mass) to represent hundreds of fibers in a yarn. They reported convergence in the projectile displacement, residual velocity and energy loss between 14 and 19 digital fiber models. In their simulations fabric was impacted with a comparatively large spherical projectile of 8 mm diameter which is one and two orders of magnitude greater than the yarn cross section and fiber diameter respectively. Rod elements do not account for the effect of Poisson's ratio hence growth in contact width and longitudinal shear deformation cannot be modeled. Grujicic et al. (2012) employed 3D beam elements to model Kevlar KM2 fibers with a user defined contact algorithm to specify the transverse properties based on the experimental load displacement relation. Similar to Wang et al. (2010) they used 1, 7, 14, 19, 24 and 30 fibers to discretize the yarn. They report that fiber transverse properties, fiber–fiber and fiber–projectile friction plays a major role in the penetration resistance and hence ballistic performance of the fabric. None of these numerical approaches have been experimentally validated through direct correlation with transverse compressive loading of a single fiber. However, the actual multi-axial loading and associated stress states and progressive failure of the individual fibers within a yarn are expected to be complex due to fiber–fiber interactions, fiber spreading and fiber deformations that develops through interactions between all 400 filaments. Therefore a rod or beam element model with 19-fibers may not be able to capture all of the important fiber-level mechanisms.

In this work we focus on understanding the transverse mechanical properties of fibers and how these properties affect the fiber–fiber deformations within a tow. The SFTCR of Kevlar fibers has been investigated by several researchers. Kawabata (1990) studied transverse compression behavior of Kevlar 29, 49 and 149 fibers of diameters 13.8, 13.8 and 11.8 μm respectively. Singletary et al. (2000a,b) investigated 1.5 and 6.0 denier Kevlar 29 fibers and (Cheng et al., 2004) studied Kevlar KM2 fibers of 12 μm diameter. The experimental results reported by these researchers indicate fibers exhibit nonlinear and inelastic response under large compressive strains. While Cheng et al. (2004) compared this nonlinear behavior to the Mullin's effect in rubber materials (Singletary et al., 2000a), attributed the observed force deflection pattern for staple fibers as cracking within the fiber cross-section, followed by closing of the cracks under compression that leads to the overall inelastic response. They also hypothesized transverse yielding followed by fibrillation for the force deflection pattern observed for 1.5 denier Kevlar 29 fibers. They also conducted FE simulation of SFTCR in terms of stresses and force deflection and reported convergence difficulties for nominal strains greater than 30% due to element distortion. However they did not report on the contact width predicted by their simulations with respect to changes in mesh density.

The schematic of single fiber transverse compression is shown in Fig. 2. The experiment involves compressing a single fiber

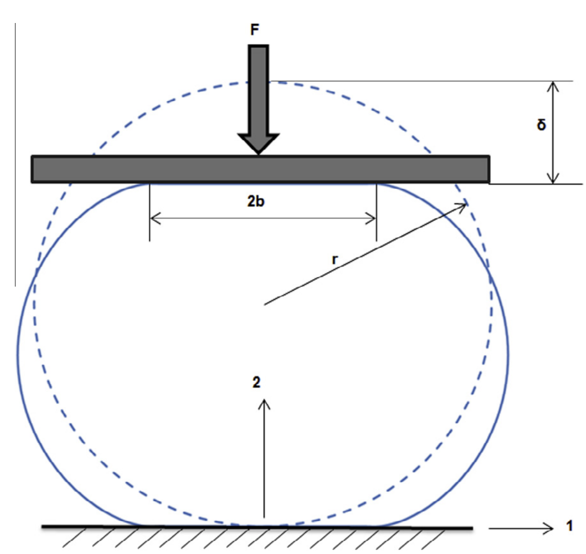

Fig. 2. Schematic of single fiber transverse compression.