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Puncture resistance of fibrous structures

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Abstract

We have developed the first comprehensive model for the study of the factors controlling the resistance of fiber fabric systems against needle puncture. Our results reveal that puncture occurs in four different stages: (i) contact pressure of the tip of the needle against a fiber strand; (ii) slippage of the tip into an inter-fiber spacing, resulting in puncture; (iii) friction of the fabric against the conical section of the needle; and (iv) slippage of the conical section through the fabric. In *multi-ply fabric systems*, we also find that the maximum force on the needle occurs during friction against its conical section (regime (iii)), i.e. *after* puncture by the tip has occurred.

Keywords: Puncture; Fiber; Kevlar; Model

1. Introduction

Several approaches have been proposed over the years to describe the resistance of fiber structures under large projectile impact [1–5]. In all these studies, the importance of fabric basis weight as well as projectile mass and velocity has been clearly identified and a good agreement with experiment was found. Resistance to needle puncture is however a much more complex problem as it also requires full consideration of the tightness of the fabric and of the sharp profile of the needle. In view of that complexity, analytical approaches cannot be used and one has to resort to numerical simulation models.

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In a previous publication [6], we presented a comprehensive numerical model for the study of the deformation and damage of woven fabrics under ballistic impact. In the approach, a single-ply fabric is represented by a two-dimensional array of nodes representing yarn crossover points. Following the original work of Roylance et al. [7], finite-difference methods are then used to solve the impulse–momentum balance equations at each crossover. That model is extended here to a detailed study of fabric resistance to needle puncture.

2. Model

Our model has been discussed at length in Ref. [6] and it is briefly summarized here. The description to follow is for an array of z plies of a woven fabric, but the approach can be easily extended to nonwoven structures. Each ply is represented by a two-dimensional lattice of nodes representing crossover points between yarns. An essential feature of our description is that individual yarns are allowed to slip over one another at crossovers. The multi-ply fabric system is clamped within circular plates and impacted *in the central node* by a needle which, in contrast to our original work of Ref. [6], is assumed to travel at a *constant* velocity, $\boldsymbol{v}_p$. A schematic of our model representation is given in Fig. 1 for a single-ply structure.

Upon impact, the two primary yarns crossing at the central node are strained by a longitudinal wave traveling at the velocity of sound

$$c = (E/\rho)^{1/2}, \tag{1}$$

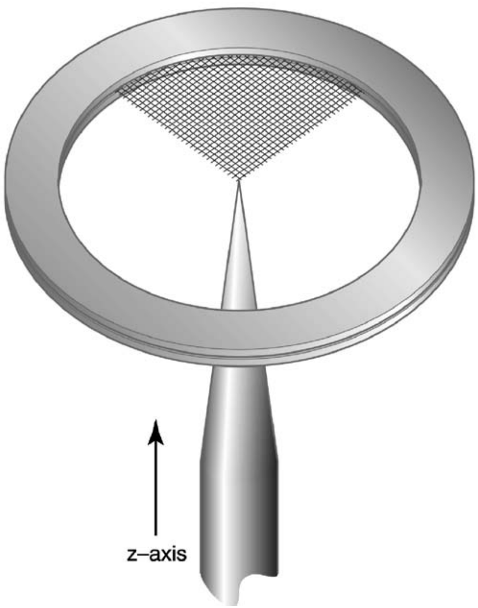

Fig. 1. Model representation of needle puncture through a plain woven fabric clamped within a ring. Only one quadrant of the fabric has been represented. The needle travels along the z-axis at a constant rate $\mathbf{v}_p$.