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Computational modeling of the probabilistic impact response of flexible fabrics

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ABSTRACT

The impact response of flexible woven fabrics is probabilistic in nature and described through a probabilistic velocity response curve or V_0–V_{100} curve. Computational impact analyses based on deterministic methods are incapable of predicting the experimentally observed probabilistic fabric impact response. To overcome this limitation we have developed a probabilistic computational framework within a finite element analysis to predict the V_0–V_{100} response. The finite element model is a yarn-based representation of the fabric architecture, with a principal stress based failure criterion implemented uniformly within each yarn, but varying for each yarn within the fabric. For each impact simulation, individual yarn strengths are mapped from experimentally obtained yarn strength distributions, resulting in fabric models with spatially non-uniform failure conditions. Impact simulations are run for the case of a spherical projectile of diameter 5.556 mm impacting a single layer of 50.8 × 50.8 mm, edge-clamped, unbacked, aramid fabric. Three different yarn strength models are implemented, representing spool yarns, and yarns extracted from greige and scoured woven fabrics. Decreases in yarn strength are found to correlate to decreases in the V_1, V_{50}, and V_{99} velocities predicted by the simulations. The relationships between yarn strength distribution and probabilistic fabric impact response are discussed.

1. Introduction

Polymeric, carbon, and glass fibers possessing high modulus, high strength, and high strength-to-weight ratios are often used in impact resistant protective systems, in the form of flexible woven fabrics and as structural reinforcements in composite structures. Typical applications include protective clothing for military and law enforcement personnel, spall liners in infantry vehicles, and turbine fragment barriers in airline fuselages. Some of the commonly used materials for these types of applications are Kevlar, Twaron, Zylon, Vectran, and S-2 glass. For many of these protective systems, the primary design requirement is preventing penetration by high kinetic energy projectiles.

Generally, the penetration behavior of fabric systems is probabilistic, exhibiting a probability of penetration at each impact velocity. This behavior can be represented by a continuous probabilistic velocity response (PVR) curve as shown in Fig. 1, or by discrete V_n values, where V is the impact velocity at which the fabric has an n% probability of being penetrated. The V_{50} velocity, at which penetration occurs during 50% of impacts, requires the fewest number of impact tests to determine experimentally. Therefore V_{50} values are often characterized and used to compare the performance of protective systems. For the design of practical protective systems, it is more preferable to determine V_1 or $V_{0.1}$ values, representing velocities at which penetration respectively occurs during 1% or 0.1% of impacts. The precise limiting V_n value used as a design point is chosen based on desired margins of safety and acceptable risks. However, compared to V_{50} characterization, considerably more experiments are required to determine these values with confidence. Fig. 1 shows notional PVRs for three different protective systems. Systems 1 and 2 exhibit identical V_{50} velocities, with different V_1 velocities. Systems 2 and 3 exhibit identical V_1 velocities, with different V_{50} values. These examples illustrate how V_{50} velocities alone can be misleading for comparing protective systems intended for penetration resistance. Instead, it is critical to characterize and consider the entire PVR curve when comparing the impact performance of different protective fabric systems.

The sources of variability that contribute to the probabilistic impact nature of fabric systems consist of parameters that stochastically vary from one fabric sample to the next and from one experimental test to the next. These parameters are either difficult to control or predict in a deterministic manner. The sources can be broadly divided into two groups: intrinsic and extrinsic. Intrinsic sources refer to the geometric and material properties of the

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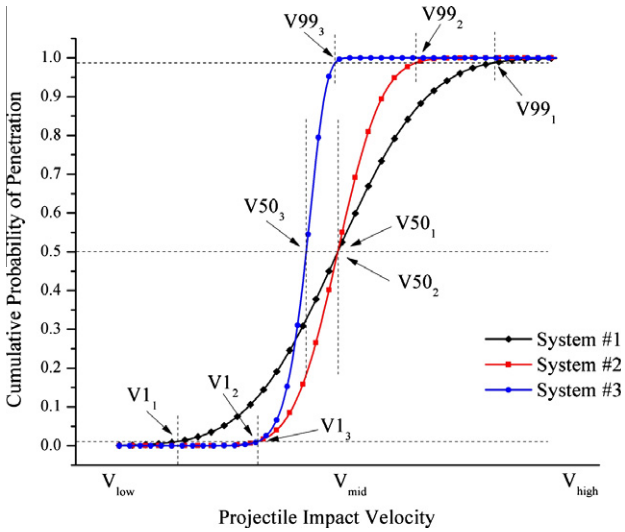

Fig. 1. Sample PVR curves.

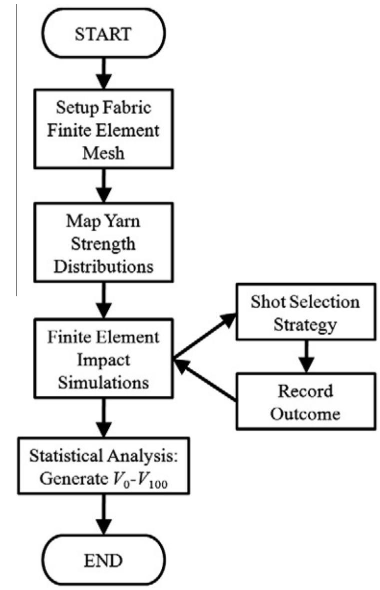

Fig. 2. Overview of the probabilistic computational framework.

filaments and yarns that comprise the fabric architecture. For example the distribution of filaments within the yarn cross section varies in arrangement from one yarn to the next, and the cross-sectional area of each of the filaments varies along the yarn length [1,29]. The material properties such as tensile modulus and tensile strength also vary from one filament to another and consequently between yarns [18]. Filament–filament and yarn–yarn frictional properties present another source of intrinsic variability. Extrinsic sources refer to all sources other than from the actual fabric system, especially those associated with the experimental impact test. These sources include, but are not limited to, variations in projectile geometry, material properties, rotation rate, obliquity, yaw, and pitch; boundary conditions, such as fabric slippage at clamped edges [20]; position of impact relative to boundaries; and position of impact relative to yarn position (at the cross-over or in-between the cross-over) [17].

A number of simulations tools have been developed for modeling the impact and penetration of fabrics, typically using a finite element analysis approach [24]. Woven fabrics have been modeled as a single homogenized membrane [8,10,28], with yarn-level architecture [4,7,31,32], and with filament-level architecture [30]. Recently multiscale models have emerged in an attempt to balance the computational requirements of the finite element model with the accuracy of predictions [3,21,22,26]. These finite element models prove very useful in investigating projectile–fabric, yarn–yarn, and fabric layer–layer interactions as well as mechanisms of deformation and energy dissipation. Parametric finite element simulations allow the effect of many factors on the impact performance to be rapidly studied such as (i) fabric architecture [16,17] (e.g. yarn geometry and undulations), (ii) yarn material properties [5,27,32] (e.g. modulus, strength, frictional coefficient), and (iii) projectile characteristics [13,25] (e.g. shape, size). The advantages of these simulations relative to experimental characterization include savings in time, labor, and material; detailed insights into the progression of stress, deformation, and failure during penetration; precise control over boundary conditions; and the ability to evaluate geometries and materials that may not be readily available for testing.

A limitation of these existing fabric impact simulation tools is that, in most cases, they have been implemented in a deterministic manner that does not result in the prediction of probabilistic penetration behavior [24]. For example, it is known from experimental testing that the tensile strength of yarns follows a statistical distribution [18]. However in the yarn-level fabric model of Duan et al. [4] all yarns in the fabric have been uniformly assigned the same failure stress of 2.3 GPa, while in Grujicic et al. [7] all yarns have been uniformly assigned the same strain-to-failure of 4%. This deterministic implementation of the yarn failure model results in identical responses during multiple runs of the same impact simulation, thereby making it difficult to capture the probabilistic penetration behavior.

In this paper, the effect of a single source of variability, statistical yarn tensile strength, on probabilistic penetration behavior (the PVR curve) is studied. To conduct this study, we implement a yarn-level finite element model representing a specific fabric type, Kevlar S706. The tensile strength distributions used in our probabilistic fabric modeling were measured experimentally and reported in Nilakantan et al. [18]. Strength models are implemented that represent as-spun (spool) yarns, warp and fill yarns in a greige fabric (spin finish intact), and warp and fill yarns in a scoured fabric (mechanically washed by the weaver to remove all finishes). These strength distributions are randomly sampled and mapped into our finite element model, creating a unique strength mapping for each impact simulation. Impact velocities are strategically varied for each impact to generate a rich set of response data (penetrating or non-penetrating response). Statistical techniques are then used to estimate best-fit, approximate PVR functions for fabrics representing spool-state, greige, and scoured conditions. Fig. 2 provides an overview of the computational probabilistic framework used in this study.

2. Computational probabilistic framework

2.1. Fabric architecture

The model fabric represents Kevlar S706 fabric, a plain weave fabric comprised of 600 denier Kevlar KM2 yarns, with a count of 34 yarns per inch in the warp and fill directions, and an areal density of 180 g/m^2. Each yarn in the real fabric is comprised of 400 circular filaments of approximately 12 μm diameter with a density of 1.44 g/cm^3.

Fig. 3 displays micrograph images of the Kevlar warp and fill yarns. The warp yarns are observed to have a greater degree of undulations than the fill yarns. This feature is important to incorporate in the model. During impact these warp yarns with greater