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Finite element analysis of projectile size and shape effects on the probabilistic penetration response of high strength fabrics

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ABSTRACT

The effects of projectile characteristics on the probabilistic impact response of single-layer fully-clamped flexible woven fabrics is numerically studied using a yarn-level fabric model with a statistical implementation of yarn strengths. Six small and large sized spherical, cylindrical, and conical projectiles of the same mass are considered. Probabilistic velocity response curves which describe the probability of fabric penetration as a function of projectile impact velocity are generated for each projectile type through a series of forty impact simulations at varying impact velocities. The probabilistic fabric impact response is observed to be strongly dependent on the shape of the projectile's impact face and the manner of projectile–yarn interactions at the impact site.

1. Introduction

High strength fabrics woven from continuous-filament aramid yarns are used in flexible protective structures because of their excellent impact performance [1]. The state of the art in finite element (FE) modeling of woven fabric impact is continually improving with recent advances in single-layer filament-level fabric modeling by Wang et al. [2], multi-layer yarn-level fabric modeling by Chocron et al. [3], and single-layer multiscale fabric modeling by Nilakantan et al. [4,5]. Yarn-level models are especially useful to parametrically study how fabric impact performance is affected by factors such as fabric architecture, yarn stiffness and strength, friction, and boundary conditions [6–11]. However, a topic that has been not been systematically addressed with simulations is the effect of the projectile characteristics such as size, shape, mass, velocity, and trajectory on the impact response of flexible woven fabrics. Some experimental studies on projectile effects have been reported [12–14], although the generality and fidelity of the results are limited by a number of factors. For example, the uncertainty introduced by fabric boundary slippage can significantly bias the fabric impact response [15]. The projectile trajectory and exact impact location are also difficult to control with precision. A further limitation of experimental testing is the inability to closely monitor and track individual yarn energy dissipations, interactions with the projectile, and yarn failure at the impact site during the impact event, all of which are important in order to fully understand how different projectiles interact with the woven fabric. These limitations can be overcome with numerical studies, thereby proving them to be a potentially useful complement to experimental investigations.

Talebi et al. [16] numerically studied the effect of the nose angle of conical shaped projectiles on the impact response of fully-clamped single-layer plain-weave Twaron fabrics and concluded that a nose cone angle of 60° provided the most penetration efficiency. Nilakantan et al. [17] studied the effect of projectile characteristics on the impact response of fully-clamped single-layer plain-weave Kevlar fabrics. One large and one small spherical, cylindrical, and conical shaped projectile with the same mass and impact velocity were considered. The conical shaped projectiles were observed to most easily penetrate through the fabric due to the tendency of these projectiles to "window" or push aside the principal yarns. The impact responses in terms of projectile velocity histories and energy transformation histories of the large spherical and small cylindrical projectiles were almost identical to each other.

One limitation of the aforementioned numerical studies is that they simulate all material, geometric, and boundary conditions deterministically, and consequently cannot predict the probabilistic impact response of fabrics. For example the tensile strengths of all yarns in these woven fabric models are assumed to be uniform and identical. However experimental studies indicate that yarn strengths are highly statistical in nature [18]. In a recent study

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Nilakantan et al. [19] developed a probabilistic computational framework that allowed the sources of variability (e.g. statistical yarn strengths) to be mapped into the fabric finite element model, which then through a series of impact simulations and a subsequent statistical analysis allowed the prediction of the probabilistic fabric impact response. The experimentally observed zone of mixed results (ZMRs) during fabric impact testing was successfully captured within this probabilistic computational framework. In this paper, the probabilistic computational framework from Ref. [19] is applied to study the effects of projectile size and shape on the impact response of fabrics. A statistical yarn strength model based on previous experimental measurements [18] is implemented to generate a probabilistic penetration response. Results from the present study are compared to the deterministic results reported in Ref. [17] to understand how projectile characteristics affect the probabilistic impact response of fabrics. Probabilistic velocity response (PVR) curves, that describe the probability of fabric penetration for a given projectile velocity, are generated for each projectile type and then compared against each other.

2. Numerical setup and methodology

With the exception of the tensile strengths assigned to the woven yarns, the details of the numerical fabric and projectile models are consistent with Ref. [17] and are therefore only briefly repeated here. Fig. 1 displays the six projectiles chosen for this study. All projectiles have a mass of 0.692 g. The spherical and cylindrical projectiles impact the fabric at the center of a yarn cross-over while the conical projectiles impact the gap in-between the yarns at the center of the fabric. The fabric considered is Kevlar S706, a fabric comprised of 600 denier Kevlar KM2 yarns plain woven at 34 × 34 yarns per inch. Fig. 2a displays the impact test setup. The preprocessor DYNAFAB [20] is used to set up the fabric mesh. The fabric is gripped on all four sides with zero slippage boundaries. The yarns are assigned a linear elastic orthotropic material model. Yarn failure is modeled via element erosion using a maximum principal stress based failure criterion. Fig. 3 displays the cumulative distribution function (CDF) used to describe the statistical yarn tensile strengths of 600 denier Kevlar KM2 spool yarns of gage length 50.8 mm obtained from the experimental work of Nilakantan et al. [18]. A 3-parameter Weibull distribution function was used to generate the CDF, and is given by

$$F = 1 - \exp\left(-\left(\frac{(S-\gamma)}{\theta}\right)^{\beta}\right) \tag{1}$$

where F represents the cumulative probability of yarn failure at a strength of S, and β, θ, and γ respectively represent the shape, scale, and threshold parameters of the 3-parameter Weibull distribution. Table 1 lists the values of these three distribution parameters, the

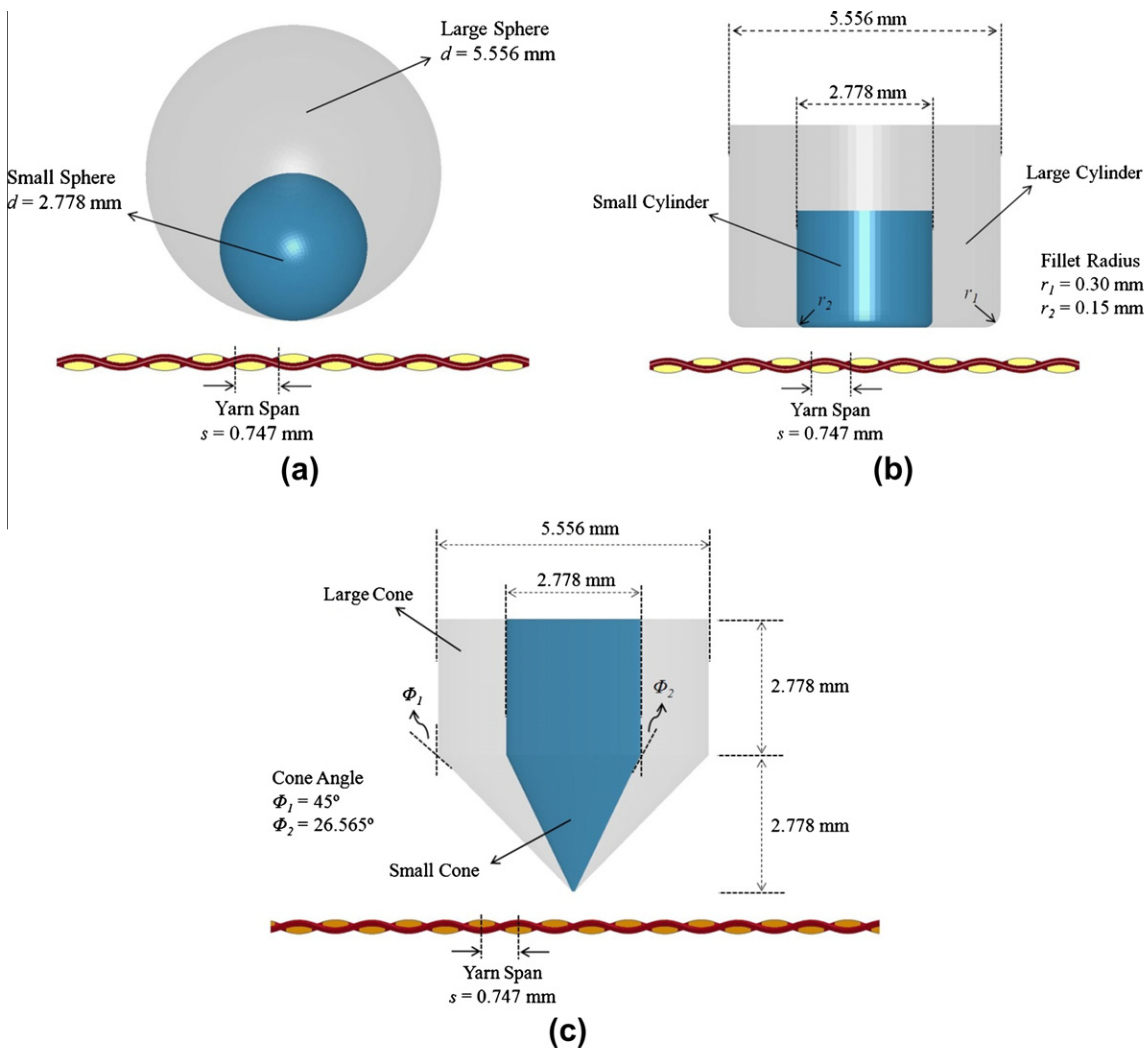

Fig. 1. Shapes and dimensions of the various projectiles used: (a) spherical, (b) cylindrical and (c) conical.